AND RELIABILITY ASSURANCE

HANDBOOK

H 56

MATERIALS AND MATERIAL PROCESSES SERIES

ARC WELDING

1 JULY 1968

OFFICE OF THE ASSISTANT SECRETARY OF DEFENSE
(INSTALLATIONS AND LOGISTICS)
WASHINGTON, D.C. 20301

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July 1, 1968

INSTALLATIONS AND LOGISTICS

Arc Welding

H 56

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For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price $3

PREFACE

The purpose of this volume on arc welding is to provide Department of Defense quality assurance personnel with the basic principles underlying arc-welding technology. All of the common arc-welding processes and techniques are discussed in this volume. Two newer welding processes--laser and electron beam--which are not arc-welding processes are also covered in this volume because of their similarity in welding application to the arc-welding processes.

The subject matter covered includes (1) a history of the development of welding, (2) the important theoretical aspects of welding including metallurgical effects and arc theory, (3) discussion of various arc-welding processes, their characteristics, importance, uses, theory, and equipment, (4) welding application criteria, and (5) quality assurance. A glossary of welding terms is included to aid the reader. A bibliography of pertinent references on welding is also included. It is intended that this volume serve as a reference in which the reader may find answers to general questions regarding arc-welding technology.

The information contained herein is presented in recognition of the need for increasing and enhancing the information available to engineering and inspection personnel so that they may better perform their assigned duties. It is hoped that such personnel will be stimulated by this publication to seek further information in more extensive works on the subject.

This handbook was prepared under Contract No. DAAG46-67-C-0051(X) by the Battelle Memorial Institute, Columbus Laboratories, Columbus, Ohio for, and in conjunction with, the Army Materials and Mechanics Research Center, Watertown, Massachusetts. Comments on this handbook are invited and should be addressed to:

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CHAPTER 1

INTRODUCTION

Section I. PURPOSE AND SCOPE

1. PURPOSE

The purpose of this volume is to provide technical guidance to Department of Defense (DOD) engineering and inspection personnel in the general field of arc-welding technology.

2. SCOPE

a. This volume contains technical and instructional data on the commonly used arc-welding processes or techniques as well as two newer welding processes, laser and electron beam.

b. Arc-welding processes for the purposes of this volume, are defined as those welding processes wherein coalescence is produced by heating with an electric arc or arcs with or without the use of filler metal.

c. The processes discussed in this volume will include all of the commonly used arc-welding processes as well as two related processes--electron beam and laser--which are not arc-welding processes. Both of these processes are similar to arc welding in several respects:

(1) Laser and electron-beam processes, like arc welding, provide high-intensity heat sources as compared with flame heat of oxy-gas processes. In fact, laser and electron beam provide higher intensity heat sources than arc-welding processes.

(2) In laser and electron-beam welding as in arc welding, there is a transfer of energy along a columnar path between the physically separated source and work.

(3) Laser and electron-beam processes are similar to arc welding since they involve the progressive formation along the weld seam of a small molten puddle which solidifies progressively to complete the joint.

Arc-welding processes such as those involving bare unshielded electrodes and carbon electrodes, which are no longer commonly employed in production welding applications will not be discussed in this volume.

d. The objectives of this volume are:

(1) To provide technical information regarding the operating theory and use of various arc-welding and related processes.

(2) To point out particular points about the specific welding processes which should be recognized by quality-assurance-minded people in order to better perform their duties.

(3) To provide basic background data on welding metallurgy and general welding technology to permit welding inspectors to converse with welding engineers and metallurgists.

(4) To promote understanding of the role of quality assurance in overall control and improvement of welded fabrications.

Section II. HISTORY

3. GENERAL

a. As this is the first volume of a series on welding, this section will cover the history of welding in general. However, the emphasis will be on arc welding; first, because it is the subject of this volume and, second, and more importantly, because arc-welding processes have grown to a position of greater importance and wider use than other welding techniques. Consequently, most recent advances have been in arc welding.

b. Welding can be traced back to the early days of recorded history. The art of metalworking is reported in the time of Egyptian Pharoahs and is mentioned often in the Old Testament of the Bible.

The first actual metal-joining process was forging which was used over 3000 years ago. The earliest forging was merely hammer welding,

probably of cold metals. By the time of the Roman civilization, however, forging was a well-developed process, together with soldering and brazing.

These latter two processes were used in many parts of the ancient world, including China, Japan, North Africa, and Southern Europe. The processes were not as we know them today, being more a casting of filler metal into joints, but they did provide a basis, in knowledge and experience, for the gas-welding industry of today.

Welding with fire was a well-established process by the time of the Renaissance. Even at that time, there were highly skilled craftsmen plying this trade. But until about 1890 ordinary fire was the principal source of heat for welding, and forge welding remained the only method of welding iron.

4. DEVELOPMENT OF MODERN WELDING PROCESSES

a. The development of electrical and gas-welding processes took many years and came about through the independent efforts of many men. Generally, the history of modern welding is traced to 1801 when Sir Humphrey Davy became the first to strike an arc between two terminals. The next important step was in 1856 when J. P. Joule worked out the relationship for electrical resistance and heating, and used it to heat and melt various materials. It was in the 1860's that metals were first intentionally joined by electricity. This was done by an Englishman named Wilde, who was granted the first electric welding patent in 1865.

b. However, it was not until 1881 that a practical use was found for the electric arc. In that year, carbon-arc street lamps were introduced. In the same year an inventor named De Meritens attempted to use the carbon arc for welding purposes. In trying to fuse parts of a storage-battery, he connected the work to the positive pole of the source of current and the carbon rod to the negative pole. Although some heat was lost in the air, enough reached the plate to fuse the metallic lead.

This carbon-arc process was further developed by a Russian, Bernardos, in the early 1880's. Unlike De Meritens, Bernardos attached the work to the negative pole and the carbon rod to the positive. His work was patented in 1887 and was in commercial use the same year. But it had the disadvantage of introducing carbon particles into the metal, making it brittle. At about the same time, the metal-arc process was developed by two men working independently, N. G. Slavianoff, in Russia, and Charles Coffin, in

Detroit. This system used a metal rod, which gradually melted adding fused drops of metal to the weld. This overcame the disadvantage of the Bernardos process.

c. Also in this same period, electric-resistance welding processes were being developed. These methods were then recognized as a faster and cheaper means of fabricating products and arc welding was confined largely to repair work. The man most responsible for the development of these processes was Professor Elihu Thomson. Thomson and his associates were issued over 150 patents pertaining to electric-resistance welding beginning in the early 1880's. However, none of the electric processes were widely accepted commercially until World War I when they were proven through their use in the war effort.

d. Taking a more prominent position in these early days were the gas-welding techniques. It was in 1836 that English chemist Edmund Davy accidently produced a carbide and its resultant gas, acetylene. From this discovery, modern gas-welding methods slowly developed. Many others worked to follow up Davy's discovery, but it was not until 1892 that a way was found to produce carbides in a quantity, and at a cost, to make them commercially acceptable. Credit for this process goes to Major J. Turner Morehead and Thomas L. Willson working at Spray, North Carolina.

Even then, acetylene was used only for lighting purposes. Then, in 1859, the findings of two men brought acetylene into the welding picture. Henry Louis de Chatelier, a French chemist, found that a very high temperature flame could be produced by using oxygen and acetylene in equal quantities. At about the same time, Dr. Carl von Linde started operating a liquid-air production plant in Germany. This was the forerunner of present oxygen-manufacturing processes.

The first successful use of an oxy-acetylene flame in welding was by Edmond Fouche, in France in 1900. By 1902, von Linde was producing commercial quantities of oxygen and in another year the new welding process was in use in European industry. Just after 1900 Fouche produced the first gas-welding torch and the process grew rapidly in the next few years. Much of this growth was due to the efforts of Augustine Davis and Eugene Bournonville. They traveled throughout the country with their equipment, taking it wherever welding problems existed. Through their personal demonstrations, they won wide acceptance for the oxy-acetylene process.

In the meantime, more and more was being learned about metals and their reaction to the acetylene flame. By 1914, compressed oxygen was available in cylinders at a much lower cost than before, and the last drawback to the oxy-acetylene process was overcome.

5. METAL-ARC WELDING DEVELOPMENT

a. As stated before, welding really was able to prove itself as a joining process during World War I, which placed great demands on industry and transportation. Prior to the war, manufacturers had said, "Never weld when you can do anything else. It is too uncertain". They had to weld during the war, and the various methods proved their worthiness.

Electric-arc welding probably profited the most. It was used particularly in the field of transportation. By use of the process for repair, the railroads were able to keep many more engines in operation. Perhaps even more important was its use in revamping 109 German ships confiscated in our harbors at the beginning of the war, but found to have been sabotaged by the Germans. This looked like an 18-month to 2-year job using what were then conventional methods. Electric-arc welding was used and all 109 ships were operating in 8 months.

b. Acetylene, meanwhile, was used more for cutting than welding in saving scrap steel and in converting and constructing ships. All processes were, of necessity, used much more extensively in industry in fabricating products for war.

c. As a result, welding became a production rather than just a maintenance tool. With this improved status, the industry really started to grow and continued to do so after the war. The most rapid growth was in arc welding as coated electrodes were developed. Oscar Kjelborg, a Swede, had first recognized the shielding potential of electrode coating in 1910. However, prior to the war, only bare, washed, or lightly coated electrodes had been used. These were good for only a few metals and weld strength was only 80 or 90 percent of the strength of the parent metal.

Because most work was being done simultaneously and in great secrecy due to patent squabbles, it is hard to fix the credit for development of electrode coatings. But the heavily coated electrodes that were produced resulted in greater penetration, lower cost, and welds with greater strength than the mild steel they joined. Another boost came with the invention of the a-c welder in 1929 by Niels C. Miller. Other major

developments between wars included the introduction of automatic wire-feeding devices between 1925 and 1928 and the introduction of the submerged-arc process in 1935. The latter was probably the greatest advance in arc welding to that time.

d. As had World War I, World War II had a profound effect on welding. This time it brought automation, which was essential because of the labor shortage and production needs of the war. Work in automation had been done prior to the war, but the equipment had never really been needed and had not been developed. Some of the major developments during the war included introduction of the stud-welding gun, aluminum spot welding, multi-arc submerged arc, and three-phase resistance welding.

e. However, probably the most significant development during this period was the introduction of gas-shielded welding. As early as 1930, a patent had been issued to Hobart and Devers for the use of an electric arc within an inert-gas atmosphere. With the pressures of the war, Russell Meredith developed its use with tungsten for welding magnesium in aircraft applications. The process, now known as GTA (gas tungsten-arc), was rapidly developed during the war with improved power sources and tooling concepts, new applications, and introduction of ac-dc welders.

f. Following closely behind GTA was the introduction of the gas metal-arc (GMA) process just after the war. This method was developed in the search for means of welding aluminum. It has since found many applications as one of the most versatile welding methods. As with other recent methods, its rapid development was due to combined efforts of many people and companies.

g. Following the war, welding continued to advance. The search now was for processes to weld high-strength steels and the new alloys for high-temperature and nuclear uses. Most of the work again was in arc welding or in completely new processes.

h. Among the advances outside of the arc-welding techniques were high-frequency resistance welding, and fluxless and vacuum brazing. One of the most important fields was that of diffusion welding. This is related to one of the oldest processes, forging, with coalescence obtained through a combination of time, temperature, and pressure. The method has been developed both here and in the USSR and allows welding of high-temperature alloys. It has been used mainly in the nuclear and rocketry fields. Cost still remains a prohibitive factor.

i. Friction welding is another important development of the post-war years. Actually, patents on the process date back to 1900, but little was done until the Russians revived it in 1956. It was not reintroduced in this country until the late 1950's but is already widely used for many products, particularly in the automotive and bicycle industries.

j. But most progress was made in the arc-welding processes. From GTA, mentioned above, grew another new process -- plasma arc. This is still used primarily for cutting and spraying, but is gaining application in welding.

k. Another important process introduced after the war was electroslag. This is a method for vertical welding of heavy structures, first used in Russia in 1949. It was originally used for shop fabrication of such things as pressure vessels, bridges, and building structures, but has since been made suitable for field use. This brought to the fore the need for a method of vertical welding of thinner materials. This need was answered by the development of the electrogas process.

l. Yet another important development during this period was the introduction of electron-beam welding. This process uses a stream of electrons to heat and fusion weld metals. Electron beams were first used as early as 1907 to melt metal. In later years, they were used for drilling, cutting, machining, etc. But it was not until 1954 that a Frenchman, J. A. Stohr, first used an electron beam to weld. Because it has been necessary to weld in a hard vacuum, this method has been quite costly and slow. However, a soft vacuum approach is being rapidly developed and much work is being done on out-of-vacuum methods. These improvements will make it a much more practical technique.

m. Today, welding continues to grow as new processes and concepts are introduced and developed. Processes that are available and in use, but have not yet been fully exploited by industry, include laser beam, ultrasonic, and explosion welding. Meanwhile, old processes are being constantly improved. This development and improvement, together with growing knowledge in the field of metallurgy, makes it possible for more and more materials to be welded with better and better quality of welds.

CHAPTER 2

ARC-WELDING THEORY

Section I. GENERAL

6. DEFINITION OF A WELD

A weld is defined as a localized coalescence of metals wherein coalescence is produced by heating to suitable temperatures, with or without the application of pressure, and with or without the use of filler metal. If a filler metal is used, it has a melting point either approximately the same as the base metal or below that of the base metal but above 800°F.

7. WELDING CATEGORIES

a. Classification. Welding, as presently practiced, can be classified into four basic categories; (1) fusion joining, (2) electrical-resistance welding, (3) solid-phase bonding, and (4) liquid-solid phase joining. These categories sometimes are named differently, but their meaning and scope remain unchanged.

b. Fusion Joining. The fusion-joining processes are those in which the parts to be joined are heated until they melt together. Pressure is not a prerequisite. Filler metal may be added to the joint and also melted and mixed into the weld metal. Examples of fusion joining are arc welding and electron-beam welding.

c. Electrical-Resistance-Welding. The electrical-resistance-welding processes might well be included among the fusion-joining processes since they ordinarily involve the melting of some metal. The quantity of metal melted, however, may be very small as compared with that melted in the acknowledged fusion-joining processes. Also, little or no fused metal may be retained in the final resistance-welded joint. Nevertheless, there are two distinguishing features of the resistance-welding processes: (1) heating is done by passage of an electric current through the parts to be welded, and (2) the use of pressure is an indispensable part of the process. Examples of resistance welding are resistance spot welding, flash welding and percussion welding.

d. Solid-Phase Bonding. The solid-phase bonding processes are those in which joining is accomplished without melting the base metals

and without the use of a liquid filler metal. Though heating is frequently employed, none of the components that form the joint ever reaches the molten condition. Pressure is always employed. Examples of solid-phase bonding are ultrasonic welding, cold welding, diffusion bonding, and friction welding.

e. Liquid-Solid Phase Joining. The liquid-solid phase joining processes are those in which the parts to be joined are heated to below the melting point and a dissimilar molten metal is added to subsequently form a solid joint upon cooling. The molten dissimilar filler metal has a melting point lower than that of the base metal being joined. The filler metal may be deposited in an open joint between the parts, or may be distributed between closely abutting faces by capillary attraction. Pressure is not required. When the assembly cools, the solidified filler metal must adhere strongly to the base metal. Examples of liquid-solid phase-joining are brazing and soldering.

8. WELD-PROCESS REQUIREMENTS

a. The welding process usually involves complex physical and chemical phenomena, varying with the nature of the weld bond produced. Optimum welding conditions vary considerably with the nature of the materials to be joined, the joint design, the welding process employed, and the service conditions to which the welded assembly will be subjected. Interactions can occur, so that critical control is often required to obtain adequate bonding and weld strength without deterioration of material properties.

b. Basic requirements for nearly all welding processes include the removal of foreign materials from the interfacial region and intimate contact between the materials to be bonded together. Failure to achieve clean surfaces or intimate contact usually results in local discontinuities in weld bonding. When clean material surfaces are brought into intimate contact under suitable conditions, weld bonds can form by processes such as solidification from the molten state, migration of interfacial grain boundaries, or diffusion.

c. There are three variables that must be controlled in most welding processes. These are time, heat, and force (in welding processes that employ pressure). All welding processes involve time variations in temperature or force. Most of these variations are rapid, with complete cycles of heating, force application, and cooling often occurring in periods as short as a fraction of a second. Thermal time constants are often

critical and dependent on material properties and geometry. Welding schedules must provide control of all variables if acceptable weldments are to be produced consistently.

9. ARC-WELDING COMPONENTS

a. The requirements outlined in the previous paragraphs are easily met in the arc-welding processes. Usually, heavy surface contaminants are removed mechanically or chemically prior to welding. A further cleaning action occurs during welding. The interfacial contaminants are removed by melting the foreign materials present, mixing them with the molten metal, and floating them to the surface of the weld. The weld bond is formed by solidification from the molten state. Pressure is generally not employed in the arc-welding processes.

b. The weld heat is generated by an electric arc and is dependent upon arc voltage, arc current, and weld travel speed. The welding arc and welding heat are discussed in greater detail in Sections II and III.

Section II. THE WELDING ARC

10. GENERAL

a. The electric arc that is used in welding is a high-current, low-voltage discharge, operating generally in the range 10-2000 amperes and at 10-50 volts. Broadly speaking, the arc constitutes a mechanism whereby electrons are emitted from the cathode, or negative pole, and transferred through a region of hot, electrically charged gas to the anode, or positive, pole where they are absorbed. The arc column usually is made up of two concentric zones as shown in Figure 1; a central plasma and an outer flame. The principal gaseous path of current conduction, the plasma, is made up of atoms of the various gases and vaporized solids available to the arc. The outer flame of the arc represents a cooler area in which atoms that have been previously electrically charged in the plasma combine with electrons to form neutral gases and give up heat. The arc column is electrically neutral; that is to say, the number of negatively charged electrons and positively charged atoms is equal. However, because the mass of the electron is only about one-thousandth of that of the lightest positive atom, most of the current is carried by electrons. Measured values of welding arc temperatures are between 8000 and 90,000 F.

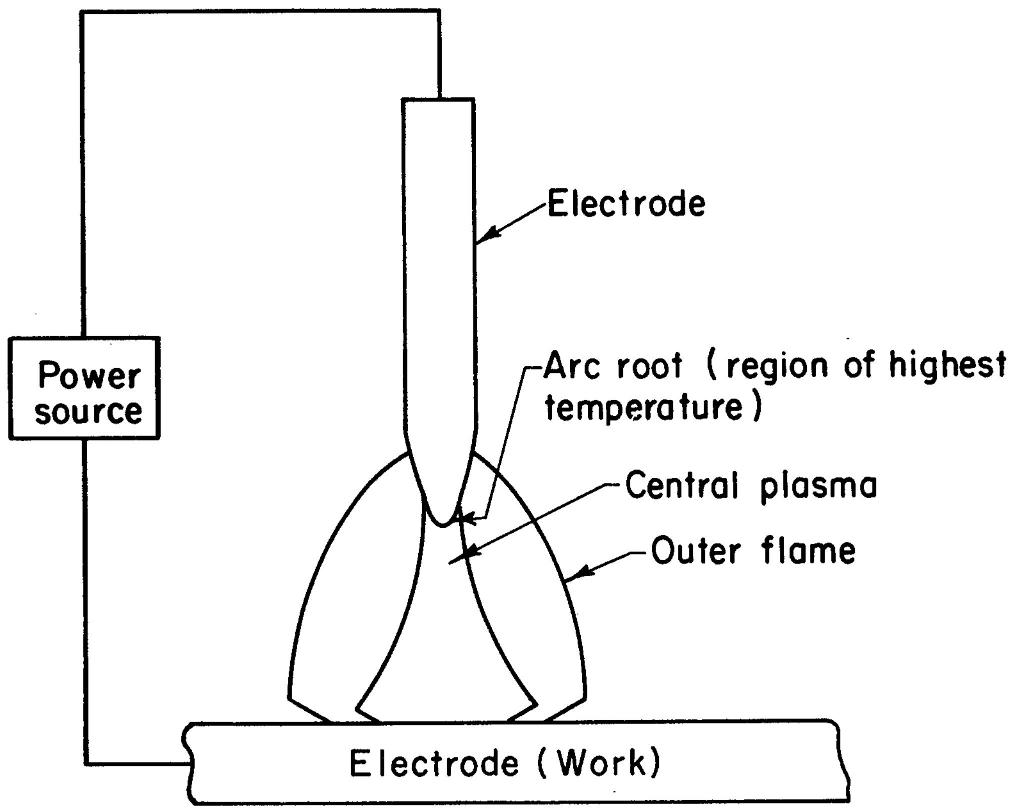


FIGURE 1. SCHEMATIC OF WELDING ARC SHOWING REGIONS OF THE ARC COLUMN

b. The distribution of heat in an arc is not uniform, but varies in the three regions (cathode, arc column, and anode). The heat liberated at the cathode and at the anode usually is greater than that from the arc column. Also, the amount of heat liberated at the cathode can differ greatly from that liberated at the anode. Whether a greater amount is liberated at one or the other depends upon the electrode material, the base metal, and the nature of the plasma. The heat distribution between cathode and anode can be an important factor in determining the melting rate of an electrode and the penetration of melting into the base metal. The importance of heat balance in welding is discussed in Section III of this Chapter.

11. THE ARC COLUMN

a. Welding arcs are usually maintained between a rod electrode and a plate workpiece. Regardless of whether the rod is positive or negative, a welding arc is constricted at the rod and spreads out toward the plate. The region in which the constricted column meets an electrode is called the arc root. The column temperature is highest where it is most constricted, in this case near the rod electrode.

b. When operating in certain gaseous atmospheres such as argon, the spread of the arc has an important consequence. It results in the formation of a jet -- called a plasma jet -- which flows along the center of the arc column toward the plate electrode. The velocity of this jet has been determined to be near 650 feet per second -- almost 450 miles per hour. Plasma jets are not formed in all gaseous atmospheres used in welding.

c. When the current flow in the plate is not uniform, magnetic forces are set up at right angles to the weld axis and may cause the arc column to deflect. This is known as arc blow. Arc blow is discussed in more detail in Chapter 4, Section II.

12. METAL TRANSFER IN THE WELDING ARC

a. Importance. The manner in which liquid metal is transferred from a consumable electrode to the weld pool may have an important effect on the usefulness of a welding process. This is particularly true when it affects the ability to weld in various positions. It may also affect the degree of penetration, the stability of the weld pool, and the amount of spatter losses.

b. Factors Affecting Metal Transfer. Of the forces which cause the transfer of metal from a consumable electrode, surface tension, gravity, electromagnetic force, and forces due to plasma velocity are the most important.

(1) Effect of Surface Tension. Surface tension is a property of all liquids, resulting from the fact that the exposed surface tends to contract to the smallest possible area, as in the spherical formation of drops. Surface tension tends to retain the liquid drop that forms on the end of the electrode in position. This is true, regardless of which direction the electrode points.

(2) Effect of Gravity. Gravity tends to detach the liquid drop when the electrode is pointed downward, and is a retaining force when the electrode is pointed upward.

(3) Effect of Electromagnetic Forces.

(a) When a current flows through a conductor such as a welding electrode, a magnetic field is set up around the conductor. The electromagnetic force on a liquid-metal drop is due to the interaction of the welding current with its own magnetic field. When the cross-sectional area of a conductor varies, as it does at the molten tip of an arc-welding electrode, the direction of the electromagnetic force is dependent upon the direction of flow of the welding current. There is a force acting in the direction of flow of the current (positive to negative) when the cross section is increasing and in the opposite direction when the cross section is decreasing.

(b) Thus, there are two ways in which the electromagnetic force may act to detach a drop at the tip of the rod electrode. When the drop is larger in diameter than the rod and the electrode is positive, the magnetic force tends to detach the drop. When there is a constriction or necking down such as may occur when the drop is about to detach, the magnetic force acts away from the point of constriction in both directions. Thus a drop that has started to separate will be given an acceleration which increases the rate of separation. These forces are shown in Figure 2.

(c) Magnetic force also sets up a pressure within the liquid drop. The maximum pressure is radial to the axis of the electrode and at high currents causes the drop to become elongated. It gives the drop stiffness and causes it to project in line with the electrode, regardless of whether the electrode is pointed downward or upward.

(4) Effect of Plasma Velocity

(a) Gas flow in the form of a plasma jet has been described in Paragraph 11b. Drops in the process of detachment

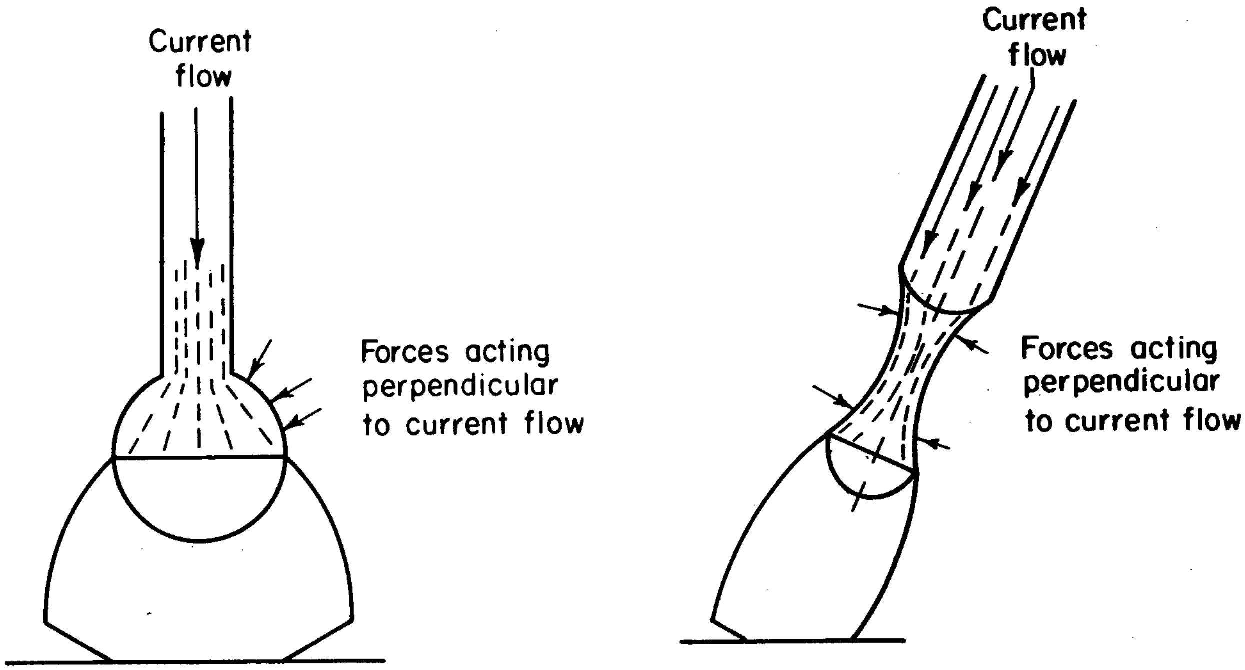


FIGURE 2. ELECTROMAGNETIC FORCES ACTING ON THE LIQUID DROP AT THE TIP OF A WELDING ELECTRODE

or in flight may be given an acceleration toward the plate electrode by such plasma jets.

(b) Rapid evaporation at the surface of a drop may produce a force away from the plate toward the rod electrode. If the current density at the electrode is sufficiently high, a portion of the heat is dissipated by evaporation of the metal. The velocity with which these vapors are given off is proportional to the rate of evaporation and inversely proportional to the area of the electrode tip. The resultant force is proportional to the square of the vapor velocity and to the area of the tip. These factors are affected in part by the electrode material, arc atmosphere, and welding current and voltage.

c. Types of Transfer. The manner in which these and other forces combine to produce various forms of metal transfer can be indicated only broadly. There are two main categories of metal transfer: free-flight and short-circuiting transfer. Free-flight transfer may be further divided into three smaller categories -- gravitational, projected, and repelled transfer. These three types of free-flight transfer are illustrated in Figure 3. Figure 4 illustrates the short-circuiting mode of transfer.

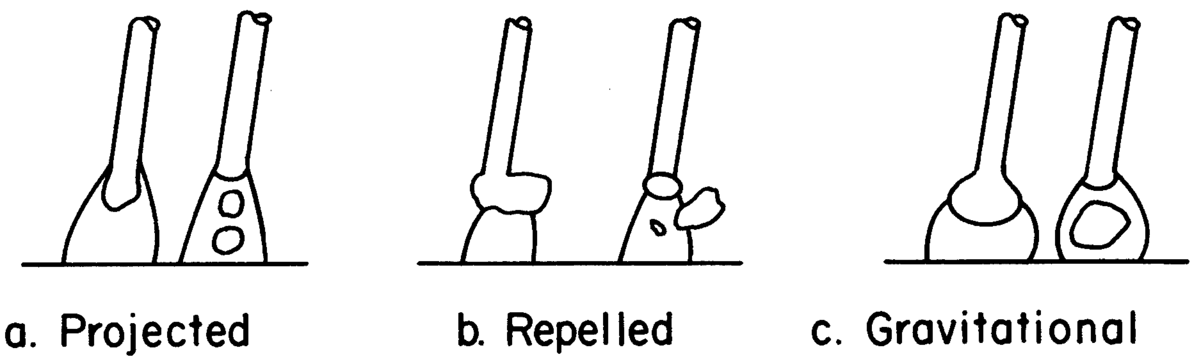


FIGURE 3. THREE TYPES OF FREE-FLIGHT METAL TRANSFER IN A WELDING ARC

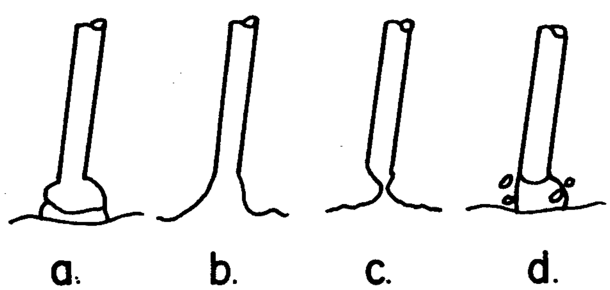


FIGURE 4. SEQUENCE OF EVENTS DURING SHORT-CIRCUITING TRANSFER IN A WELDING ARC

a. Globule of molten metal builds up on end of electrode
b. Globule contacts surface of weld puddle
c. Molten column pinches off
d. Just after pinch-off fine spatter may be given off.

(1) Free-Flight Transfer. In free-flight transfer, the liquid drops which form at the tip of the consumable electrode are detached and travel freely across the space between the two electrodes before plunging into the weld pool. When the transfer is gravitational, the drops are detached by gravity alone and fall slowly through the arc column. In the projected type of transfer, other forces give the drop an initial acceleration and project it independently of gravity towards the weld pool. During repelled transfer, forces acting on the liquid drop give it an initial velocity directly away from the weld pool.

(2) Short-Circuiting Transfer. With short-circuiting transfer, the tip of the growing drop of liquid metal makes contact with the weld pool before it is detached and causes a short circuit. Surface tension and electromagnetic forces then draw the liquid into the weld pool and in so doing, break the short circuit and allow the arc to be re-established.

13. METAL TRANSFER IN GAS METAL-ARC WELDING

a. The gravitational and projected modes of free-flight metal transfer may occur in the gas metal-arc welding of steel, nickel alloys, or aluminum alloys using a direct-current, electrode-positive (reverse polarity) arc of properly selected types of shielding gases. At low currents, wires of these alloys melt slowly. A large spherical drop forms at the tip and is detached when the force due to gravity exceeds that of surface tension. As the current increases, the electromagnetic force becomes significant and the total detaching force increases. The rate at which drops are formed and detached also increases. At a certain current, a change occurs in the character of the arc and metal transfer. The arc column, previously bell-shaped or spherical and having relatively low brightness, becomes narrower and more conical and has a bright central core. The droplets which form at the wire tip become elongated due to magnetic pressure and are detached at a much higher rate.

b. When carbon dioxide is used as the shielding gas, the type of metal transfer is much different. At low and medium currents, the drop appears to be repelled from the plate electrode and is eventually detached while moving away from the plate electrode and weld pool. This gives rise to an excessive amount of spatter. At higher currents, the transfer is less irregular. By reducing the arc voltage, it is possible to reduce the arc length so that the liquid drop touches the weld pool before becoming detached and enters the short-circuiting type of transfer. Excessive spatter may be avoided by proper adjustment of the welding variables. Short-circuiting transfer is sometimes known as dip transfer.

14. METAL TRANSFER IN THE FLUX-SHIELDED PROCESSES

The transfer of metal when welding with coated electrodes is generally of the short-circuiting type. Some free-flight transfer of small droplets may also occur. One exception to this rule occurs with the iron oxide-coated carbon steel electrode in which the transfer is of the projected type. A great deal of gas is given off in the liquid metal produced by this electrode, and it may be that this gas is responsible for the projected transfer. Transfer in the submerged-arc process is of the free-flight type. The types of metal transfer in the flux-shielded gas metal-arc and submerged arc welding processes are summarized in Table I.

Table I. TYPES OF METAL TRANSFER IN THE SHIELDED METAL-ARC, GAS METAL-ARC, AND SUBMERGED ARC WELDING PROCESSES

Process	Current	Arc Length	Transfer Type
Shielded Metal-Arc			
Iron oxide type electrodes	Normal	Normal	Free flight (projected and gravitational)
Cellulosic, rutile, or basic electrodes	Normal	Normal	Short-circuiting
Gas Metal-Arc			
Argon or argon-oxygen shielding	Low	Long Short	Gravitational Short-circuiting
Ditto	High	Normal	Projected
Carbon dioxide shielding	(All)	Long Short	Repelled* Short-circuiting
Submerged Arc	Normal	Normal	Free flight

*At high currents, the transfer is sufficiently directional for CO_2-shielded welding to be used in the free flight mode.

15. GASES IN MOLTEN METALS

a. The atmosphere in which we live is composed of about four-fifths nitrogen and one-fifth oxygen. When most metals are exposed to air, they have a strong tendency to combine with oxygen, and to a lesser extent with nitrogen. This tendency is especially strong when the metals are in the molten condition. The rate of oxide formation will vary with the different metals, but even a thin film of oxide on the surface of metals to be welded can lead to difficulties. The oxides generally are relatively weak, brittle materials that in no way resemble the metal from which they are formed. A layer of oxide can easily prevent proper bonding of two pieces of metal during welding. If quantities of oxide are entrapped in the molten weld pool, the strength of the joint may be lowered greatly. Molten droplets from an electrode may become coated with oxide during transfer to the weld joint and may dissociate and dissolve in the molten metal, causing serious embrittlement of the weld.

b. The ill effects of nitrogen are not as widely recognized because they are often overshadowed by the oxide problems. However, many metals will react with nitrogen to form a metal nitride. This compound may exist as a surface film or, like the oxide, become entrapped in the metal. Nitrogen may also dissolve in the molten metal and cause weld embrittlement.

c. Hydrogen absorbed in molten metal may also cause problems in the welded joint. Some metals absorb large quantities of hydrogen when molten. Upon solidification, the metal cannot retain all of the hydrogen and it is forced out of solution.

(1) In low-alloy steels the hydrogen coming out of solution sets up stresses within the metal and, when large amounts of hydrogen are present, may cause cracking of either the weld or the heat-affected zone. The cracks do not occur instantaneously on cooling, but develop over a period of time. Cracking may start at any time from a few seconds to several days after solidification of the weld metal, and may continue to develop for 24 hours or more. Initially, the cracks are very fine and short, but gradually extend in length and width, at the same time evolving hydrogen.

(2) Hydrogen is particularly harmful in aluminum welds. Aluminum has a high solubility for hydrogen in the molten condition but this solubility decreases drastically when the metal solidifies. When the molten weld metal containing dissolved hydrogen begins to solidify, the hydrogen forms gas bubbles which, if they do not escape to the surface of the weld, may become entrapped in the solidified weld as porosity.

d. It can be seen that it is very important to prevent gases combining with the molten metal during welding. It is also important to remove the gases already dissolved in a metal from the molten weld pool. Two methods used to shield the molten weld from the atmosphere are (1) slag covering and (2) gas shielding. Deoxidizing elements are added to the rod coatings or the welding electrode wire to combine with oxygen and cause it to float to the surface as a slag.

16. WELD SHIELDING IN THE SHIELDED METAL-ARC WELDING PROCESS

a. In shielded metal-arc welding, the electrode is a wire or rod with a relatively thick covering made of organic or inorganic materials, or a mixture of both. This covering is carefully formulated so that during welding it can perform several functions. It gives off gases which prevent air from getting at the arc and the molten metal. The covering provides deoxidizing or fluxing agents and slag formers which (1) combine with and remove oxygen, (2) control the viscosity of the molten weld, and (3) blanket the solidifying weld metal, thereby protecting it from oxidation and retarding its cooling. The covering also contributes alloy elements to the weld metal, either to make up for those which are partially consumed in the arc or to add new ones. A further function of the covering is arc stabilization.

b. During welding, the heat of the arc concentrates on the core wire. Consequently, the core melts ahead of the coating so that the coating protrudes beyond the end of the core. This provides a mechanical shield for the electrode tip.

17. WELD SHIELDING IN SUBMERGED-ARC WELDING

a. In submerged-arc welding, the weld is shielded by a blanket of granular material on the work. The heat produced by the arc melts the immediately surrounding granular material so that it forms a subsurface molten pool of glassy slag which surrounds the arc and is kept molten by the continued heat of the arc. The granular material completely covers the molten pool and is fed continuously as the work progresses.

b. The granular, fusible materials used for shielding with submerged-arc welding are made to several chemical specifications. The ingredients are generally silicates to which powdered metals have been added. The metals enter the weld deposit during the melting operation. All of the shielding materials used in making the weld are selected for minimum evolution of gases during welding. The hydrogen content is very low.

18. WELD SHIELDING IN THE INERT-GAS PROCESSES

In gas metal-arc and gas tungsten-arc welding, shielding is obtained from inert gas. The inert gas flows from an inverted cup around the electrode and protects the electrode, the arc stream, and the molten metal in the weld pool from the adverse effects of oxygen and nitrogen in the air. Usually, argon or helium or mixtures of these gases are used as the shielding gas. The gases do not chemically react with the weld metal; they simply displace the air around the arc. No flux is required since no oxides are formed.

19. WELD SHIELDING IN OTHER PROCESSES

a. Electron-Beam Welding. The weld is shielded by a vacuum in electron-beam welding. Thus, there is no oxygen, nitrogen, or hydrogen present in the atmosphere to combine with the liquid metal.

b. Laser Welding. Since the laser delivers its energy in the form of light, it can be operated in any transparent environment. Therefore, laser welds may be shielded by a vacuum, by inert gases, or by other atmospheres that cannot be used in the open-arc welding processes.

Section III. WELDING HEAT

20. HEAT SOURCES

a. Heat may be generated for welding by a number of methods:

(1) Electric arc maintained either between an electrode and the work or between two electrodes.

(2) Resistance heating obtained by passing an electric current through the parts to be joined. The electric current may be introduced into the parts by placing them in series in an electric circuit or by inductive coupling in an electric circuit.

(3) Flame heating with a torch in which oxygen and a hydrocarbon gas are mixed and burned. Oxygen and acetylene mixtures are commonly used.

(4) Furnace heating.

(5) Impingement of a high velocity stream of electrons as in electron-beam welding.

(6) Chemical reaction of powders which release excess heat upon reaction, as in thermit welding.

(7) Impingement of a high-energy light beam on the metal surface, such as in laser welding.

(8) Mechanical methods such as heat of friction or explosive impact.

b. The most widely used heat sources for welding are the electric arc and resistance heating in that order, and most of the welding theory is based on these two types of heating.

21. FUNCTIONS OF WELDING HEAT

a. In most welding processes, and in all of the processes discussed in this volume, heat is used to melt the base metal and filler metal to form the weld.

b. The primary function of the welding heat is to increase the atomic mobility of the metal parts being joined. In processes involving metal, an additional function is to assist in the destruction of surface films of foreign materials on the faces of the parts to be joined.

22. DETRIMENTAL EFFECTS OF WELDING HEAT

a. Welding heat can have a number of detrimental effects:

(1) Loss of strength in the weld heat-affected zone (HAZ). In certain materials, for example, those which are strengthened by cold working, the heat of the weld can cause softening of the base metal adjacent to the weld, i.e., the weld-heat-affected zone.

(2) Loss of ductility in the HAZ possibly leading to cracking. In steel, for example, the welding heat can cause changes in metal structure to produce martensite, a high hardness metal phase which can lead to cracking in the region of the HAZ.

(3) Deterioration of toughness properties. The HAZ structure may have low toughness properties so that, if cracks are formed, they can propagate under low applied stresses.

(4) High residual stresses. The localized heating at the weld can cause differential shrinkage stresses which can lead to distortion and, in some materials, increase susceptibility to corrosion.

23. CONTROL OF WELDING HEAT--HEAT BALANCE

Heat applied during welding must be controlled carefully if optimum useful effects are to be obtained in the weld with a minimum of harmful side effects. Heat balance is usually an important consideration. In fusion welding, for example, sufficient heat must be supplied to each side of the interface to melt the surfaces and permit a weld to be made. In addition, when filler metals are added, sufficient heat must be provided to melt the filler wire at a rate sufficient to fill the weld groove. The total heat must be distributed appropriately to produce the desired melting of the base metals and filler metal. In most applications, loss of heat through the base material is an important factor in resultant temperature distributions. The base materials on either side of the interface may vary widely in heat capacity, thermal conduction, or melting temperature. These material properties and geometric effects must be compensated for by control of heat inputs to various weld areas. In the case of similar materials joined in areas of equal section and comparable geometries, input heat must be balanced between adjacent interfacial areas to obtain optimum weld symmetry and fusion bonding.

24. WELD ENERGY INPUT IN ARC WELDING

a. Not all of the heat generated in the arc can be effectively used in fusion welding. Values for the efficiency of heat utilization vary from 70 to 85 percent in the metal-arc welding process. For the carbon-arc process, efficiencies are somewhat lower, ranging from 50 to 70 percent, while 80 to 90 percent efficiencies are obtained in the submerged-arc welding process. The balance of the heat is lost by radiation from the arc, by spatter, by heating of the unmelted base material, and by escape to the surrounding air.

b. The heat developed by an arc, referred to as "weld energy input", can be calculated using the expression

$$H = \frac{ExIx60}{S},$$

where H - energy input in joules or watt-seconds per lineal inch of weld
E - arc voltage, volts
I - arc current, amperes
S - travel speed, inches/minute.

This energy input parameter can be used to make comparisons in welding studies involving low weld travel speeds, e.g., up to about 10 inches per minute with covered electrodes. With higher travel speeds, the efficiency of heat transfer in the fusion zone is increased and the use of the energy input parameter may not be justified.

25. TEMPERATURE DISTRIBUTION IN ARC WELDING

a. Typical temperature distributions during the deposition of bead welds on thin and very thick plates are shown in Figure 5. The distributions are those which an observer would notice if stationed at the source of heat during welding. This source, the arc, is at the center of the isotherm of highest temperature.

b. As shown in Figure 5, the rise of temperature in front of the heat source is more rapid than the fall of temperature behind the source. This is brought about by the movement of the heat source relative to the flow of heat in the plate. The influence of thickness may also be noted. For identical welding conditions, a wider heat-affected zone is created in the thinner plate than in the thicker plate.

26. CONTROL OF COOLING RATE--PREHEATING AND POSTHEATING

a. Cooling rates can be a very important factor when welding certain alloys. Rapid cooling from high-temperature ranges can result in the formation of very hard structures in the heat-affected zones in such materials as high-carbon or alloy steels. These structures lower the toughness and ductility of the weld, and the heat-affected zones and special precautions must often be taken to control cooling rates in critical applications.

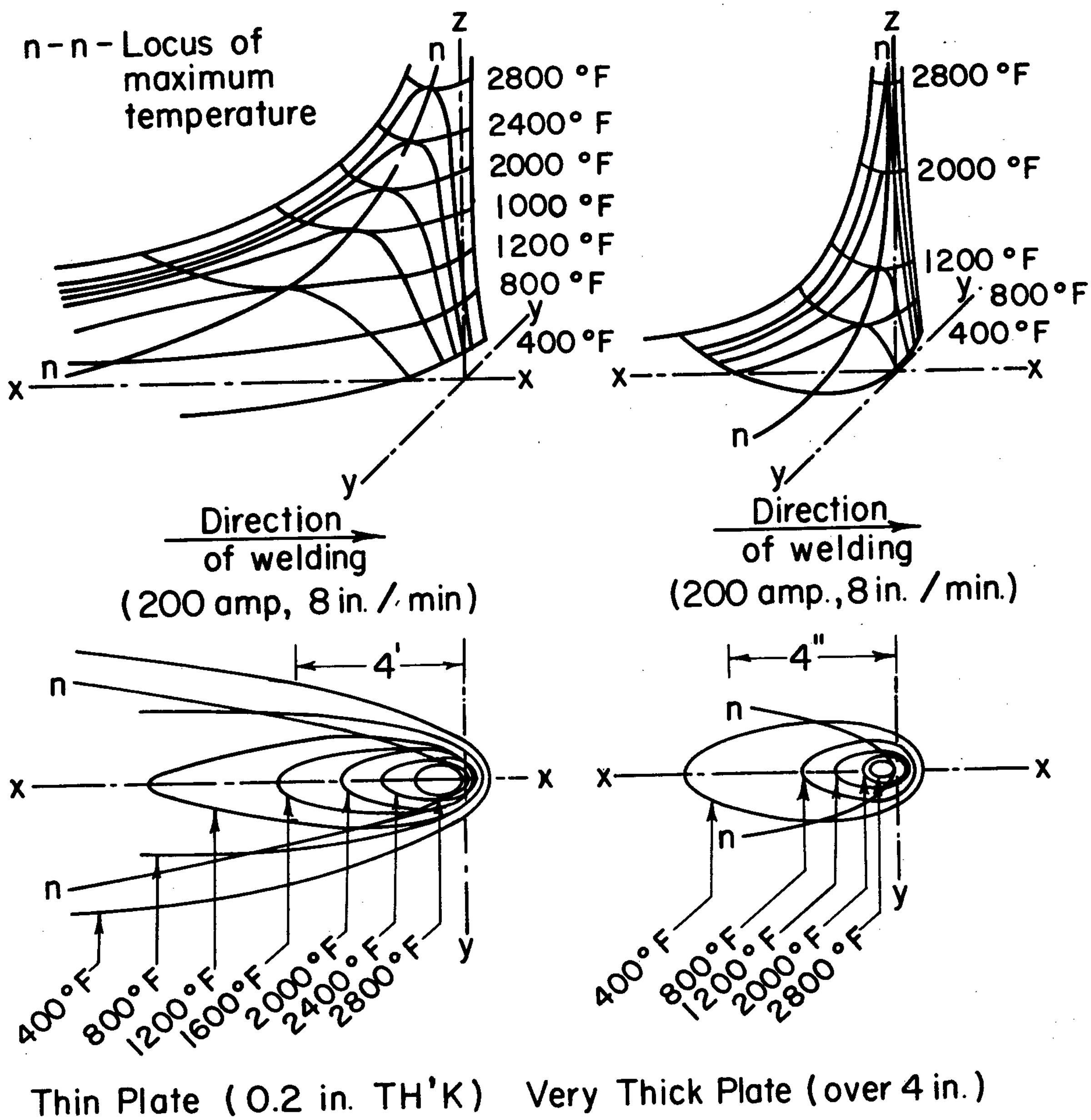


FIGURE 5. TEMPERATURE DISTRIBUTION ON THE SURFACE OF THIN (left) AND VERY THICK (right) PLATES DURING METAL-ARC WELDING

b. Use of high energy input, i.e., high welding currents and low travel speeds, in arc welding promotes slow cooling. Also, thick plates and low plate temperatures promote rapid dissipation of heat and therefore increase the cooling rate.

c. Three methods used to decrease cooling rates are (1) preheating the adjacent base materials to reduce the rate of heat loss during and after welding, (2) using slower travel speeds to increase heat input and permit the adjacent materials to rise to higher temperatures during welding, so that they cool more slowly, and (3) postheating, in which the heat of the weld is continued by external heating to limit cooling rates.

d. Postheating may also be used to correct some of the harmful effects of welding after the weld is completed by annealing, tempering, or stress relieving. Such postweld heat treatments may be local, as in induction heating of weld areas only, or may involve the entire structure, as in the furnace heating of welded assemblies.

27. PREHEAT AND POSTHEAT

a. General. Low-carbon and structural steels seldom require preweld or postweld heat treatment, unless to assure machinability or prevent warpage. The weld deposit and heat-affected zone of high-carbon or alloy steels may contain a high percentage of martensite. The benefits and effects of preheat and postheat treatments are discussed in Chapter 2, Section III.

b. Preheating. There is a simple method for determining preheat requirements in welding steels. The hardenability of a steel is approximately related to its carbon content and to the content of certain other alloying elements. The approximate amount of the other alloying elements that produce the same hardness as 1 percent carbon is known. Thus, an indication of the hardenability can be calculated as follows:

$$\text{Equivalent Carbon Content} = \%C + \frac{\%Mn}{6} + \frac{\%Ni}{15} + \frac{\%Mo}{4} + \frac{\%Cr}{5} + \frac{\%Cu}{13}$$

This formula is valid when the percentages are within the following ranges:

Carbon, less than 0.50 percent
Manganese, less than 1.60 percent
Nickel, less than 3.50 percent
Molybdenum, less than 0.60 percent

Chromium, less than 1.00 percent
Copper, less than 1.00 percent

Table II shows the suggested preheat temperatures for different values of equivalent carbon content. Some steels may require postheat as well as preheat. This is particularly true for those having equivalent carbon contents greater than 0.60 percent and for welding in heavy sections.

c. Postheating. Postheating, in this case, refers to heating immediately after the weld is made. It differs from treatments made after the weld cools, such as stress relieving, tempering, and annealing. It serves the same purpose as preheating by slowing the cooling action. Postheat is seldom used alone, but generally in conjunction with preheat. Postheat is most often used on the highly hardenable steels when adequate preheat is difficult to attain because of the size of the sections being welded.

Table II. PREHEAT REQUIREMENTS BASED ON EQUIVALENT CARBON

Equivalent Carbon, %	Recommended Treatment
Up to 0.45	Preheat optional
0.45 to 0.60	Preheat at 200 to 400 F
Above 0.60	Preheat at 400 to 700 F

28. INFLUENCE OF OPERATING PARAMETERS ON WELD BEAD SHAPES

a. General. The welding current, arc length, travel speed, and electrode diameter have a marked effect on the wire-melting rate, penetration, and arc stability in all processes. In gas metal-arc and submerged-arc welding, the electrode extension (stick out) also has an effect. The type of shielding gas affects the weld-bead shape in gas metal-arc welding.

b. Effect of Welding Current. The depth of weld penetration and size of the weld reinforcement are directly dependent upon the magnitude of the welding current. Penetration and the amount of weld reinforcement increases as the current increases when all other variables remain constant. In most arc-welding processes (except gas tungsten arc), penetration is lower with direct current, straight polarity (electrode negative) than with direct current, reverse polarity (electrode positive).

c. Effect of Arc Length. Some control of the weld penetration and width can be gained by regulating the arc length. A short arc is more penetrating than a long arc, and it produces a weld nugget and reinforcement that is relatively higher and narrower than one developed with a long arc. The amount which the arc length can be changed is limited, however. An arc which is too long or too short is generally unstable and may result in weld porosity.

d. Effect of Travel Speed. Weld penetration and the size of the weld bead are generally inversely proportional to the travel speed when other welding variables are held constant.

e. Effect of Electrode Diameter. The size of the weld bead is to some extent determined by the electrode diameter. With small-diameter electrodes, low welding current can be used to deposit smaller welds. For the same current, the arc becomes more penetrating and the deposition rate increases as the electrode diameter decreases.

f. Effect of Electrode Extension. In processes which use a spooled wire electrode, the distance between the contact tip and the arc is called the electrode extension or "stick out". When this distance is increased, more energy is used in preheating the wire, thereby increasing the burnoff rate. Long extension is used in overlay welding to achieve a high deposition rate with a low current, so that penetration into the base metal is minimized. Use also has been made of long extension to permit higher welding speeds without increasing the welding current when penetration is not important.

g. Effect of Shielding Gas. The type of shielding gas used for the gas-shielded arc-welding processes has a pronounced effect on weldbead shape and penetration, as well as arc characteristics. Both argon and helium have been used as shielding gases for welding. Because much more spatter is produced with helium than with argon, the use of helium for ferrous applications has been relatively small compared to the use of argon. Oxygen or carbon dioxide is added to the shielding gas almost invariably when direct current reverse polarity is used, since the addition improves the arc stability, minimizes undercut, improves the appearance of the weld bead, and reduces the depth of the central finger that is characteristic of the weld penetration obtained with gas metal-arc welding. Oxygen is a necessary addition for operation with direct current straight polarity if a stable arc is to be achieved with a bare electrode. Helium has been added to the argon to increase the weld penetration while retaining the desirable transfer characteristics of argon.

SECTION IV. ARC WELD STRUCTURE

29. ZONES IN ARC WELD

a. An arc weld consists of three zones: the weld metal, the heat-affected zone (HAZ), and the unaffected base metal. These three zones are shown in Figure 6.

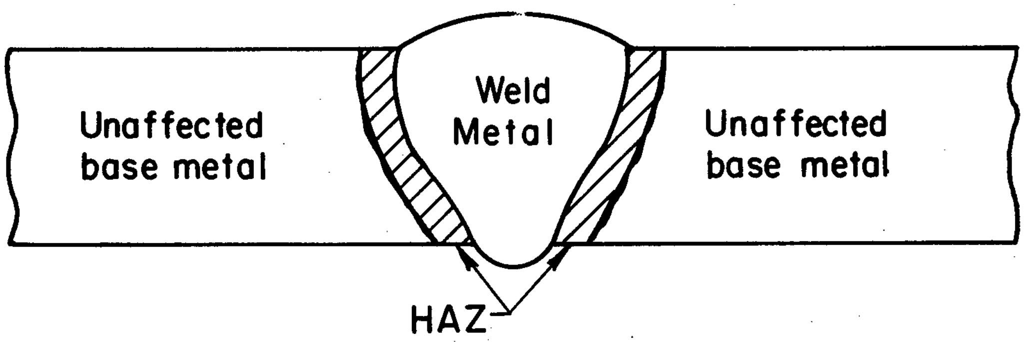


FIGURE 6. THREE BASIC METAL ZONES IN AN ARC WELD

b. The weld metal is that portion of the weld which has been melted during welding.

c. The heat-affected zone is the portion of the base metal which has not been melted but whose mechanical properties or microstructures have been altered by the heat of welding or cutting. During welding, the temperatures in the HAZ range from the melting point of the base metal to the ambient plate temperature.

d. The unaffected base-metal zone is that portion of the base metal wherein the welding heat did not exceed the minimum required to affect structure or properties.

30. OTHER IMPORTANT WELD FEATURES

a. In addition to the three basic zones in a weld, there are several other weld features which should be recognized. These are illustrated in Figure 7, and are defined below.

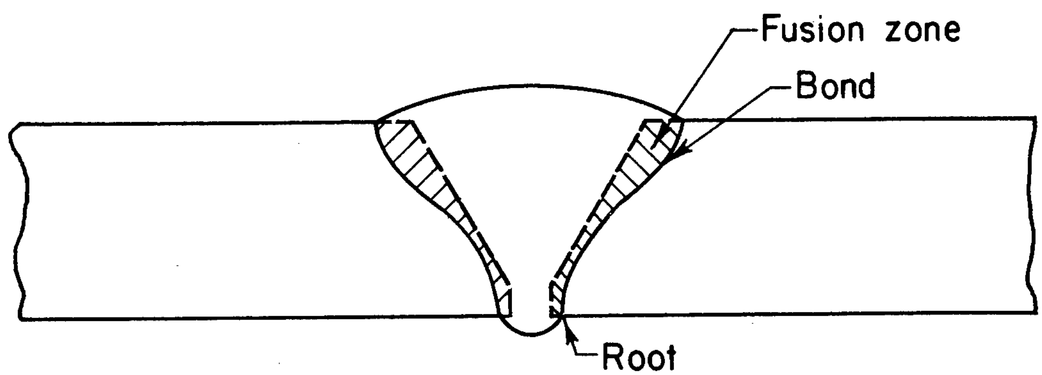


FIGURE 7. FUSION ZONE, BOND, AND ROOT IN AN ARC WELD

b. Fusion Zone: the area of base metal melted as determined on the cross section of a weld.

c. Root Of The Weld: the points as shown in a weld cross section at which the bottom of the weld intersects the base metal surfaces.

d. Bond: the junction of the weld metal and the base metal or the junction of the base metal parts when weld metal is not present.

31. WELD-METAL ZONE

a. The composition of the weld metal and the conditions under which it freezes have a strong influence on the ability of weld metal to form a sound, serviceable joint. The composition may be that of the base metal or it may be a mixture of filler metal and base metal in proportions up to nearly all filler metal. In arc welding, the molten weld-metal pool is considerably superheated and is exposed to the various gases present in the arc atmosphere. As the arc moves on, the weld metal is cooled by the adjacent metal at rates that vary from relatively low to extremely high. Also, the nature of the joint may be such that considerable restraint is imposed on the weld metal during freezing and cooling. All of these factors affect the characteristics of the weld metal obtained.

b. A single-pass weld has a cast structure similar to that of an input or other casting. If examined under a microscope, it would show elongated grains or columns beginning at the edge of the molten zone and directed toward the center line of the weld. A columnar structure of this type is likely to have weaknesses in directions parallel to these columns. In

multiple-pass welds, the as-cast structure of the weld beads are exposed to the heat of each succeeding weld pass and undergo reactions which tend to alter the as-cast structure.

32. THE UNAFFECTED-BASE-METAL ZONE

In producing plates from ingots, the columnar structure of the ingot is broken up to a more rounded and even size and the weaknesses of the cast structure are reduced. The method in which an ingot is reduced to a more usable form affects many of the mechanical properties of a material. These properties include the ultimate strength, yield strength, impact strength, hardness, ductility, and others. These properties may sometimes vary with the direction in which they are tested in the same piece of material Also, they are often changed by heating and cooling.

33. THE BASE-METAL HEAT-AFFECTED ZONE

a. The base metal in the vicinity of a weld is subjected to a complex thermal cycle in which peak temperatures, ranging from the melting point down to room temperature, are involved. The change in structure of the metal which is brought about by welding is determined by either or both of the following: (1) the maximum peak temperature experienced and (2) the rate at which the metal cools from high temperature. Practically all metals are sensitively influenced by the peak temperature, but only a few are sensitive to the cooling rate as well.

34. EFFECT OF WELD HEAT ON VARIOUS TYPES OF BASE METALS

a. There are too many types of base materials to consider each one in detail here. They may, however, be grouped into three general classes: (1) non-heat-treatable materials, (2) materials hardened by changes in metal structure such as a hardenable steel, and (3) precipitation- or age-hardenable materials.

b. The microstructures that occur in a weldment are related to the maximum temperature attained by the material and to the rate of heating and cooling. The changes which take place in the microstructure will be discussed in relation to hardness, since hardness is related to tensile strength and microstructure of metals in a rather well-understood way. The following discussion assumes that the filler metal added is the same as the parent metal. It should be stressed that the material groupings are very general and that peculiarities of specific materials are not considered.

35. ANNEALED MATERIAL - NON-HEAT-TREATABLE

a. If two pieces of annealed material such as brass or pure aluminum are joined by fusion welding, the hardness distribution across the weld is as shown in Figure 8a. The fusion or weld zone is indicated along with the region adjacent to the fusion zone where grain growth has occurred. The fusion zone has an as-cast structure and is therefore softer than the rolled and annealed base plate.

b. The region next to the fusion zone that was heated to a temperature near the melting point shows characteristic grain growth from the welding heat. Coarse-grained structures are slightly softer than fine-grained structures, so that the hardness in the heat-affected region is slightly lower than that of the parent plate.

36. WORK-HARDENED MATERIAL - NON-HEAT-TREATABLE

If the plates of materials in the preceding example had been cold rolled rather than annealed, a hardness distribution such as shown in Figure 8b would have been found. Here the plate is much harder than the weld; the hardness is determined by the percentage of cold reduction. As the weld region is approached, the hardness begins to drop. The first drop is a result of the relief of internal stresses by low temperatures. Closer to the weld, where the maximum temperature was higher, the cold-worked material is annealed and thereby softened. The degree of softening increases with increase in maximum temperature to which the metal is heated. The HAZ therefore becomes progressively softer as we approach the bond. Grain growth is pronounced in the area next to the bond, which means that this region is even softer than the area only annealed. Finally, the softest area of all is the cast structure of the weld metal itself.

37. HARDENABLE STEEL

a. The hardness distribution of a weld in a hardenable steel is shown in Figure 8c. The base metal is assumed to be in the annealed condition and therefore is relatively soft. The highest hardness occurs in the martensitic region of the heat-affected zone. This region is generally very brittle and has very little ductility. The weld metal and other regions in the HAZ will probably contain martensite mixed with other softer phases and therefore will be lower in hardness.

b. The harmful effects of martensite in the heat-affected zone are well known. Much expense is encountered in an effort to prevent its formation or to temper it to lower hardness after welding. Preheating the

n will decrease the cooling rate and thus decrease the likelihood of .rtensite formation. Postheating, on the other hand, will temper any .nartensite that has formed and reduce its hardness. Likewise, in multipass welding, succeeding passes will temper and soften any martensite formed in the passes previously deposited. The last pass deposited, however, will be untempered.

38. PRECIPITATION HARDENABLE MATERIALS

a. A hardness traverse across a weld in a precipitation hardenable material, such as an aluminum alloy, is shown in Figure 8d. These materials are hardened by an aging treatment which consists of holding the material for a time at room or slightly elevated temperature. The aging treatment causes submicroscopic particles to precipitate in the metal structure, which cause hardening of the material. If overaged at higher temperatures or for longer times, the particles become larger and the hardness decreases.

b. In Figure 8d, it is assumed that the base metal has been hardened prior to welding. The welding heat therefore causes softening in the heat-affected zone due to overaging. The weld metal is also softer than the base metal since it has not been aged.

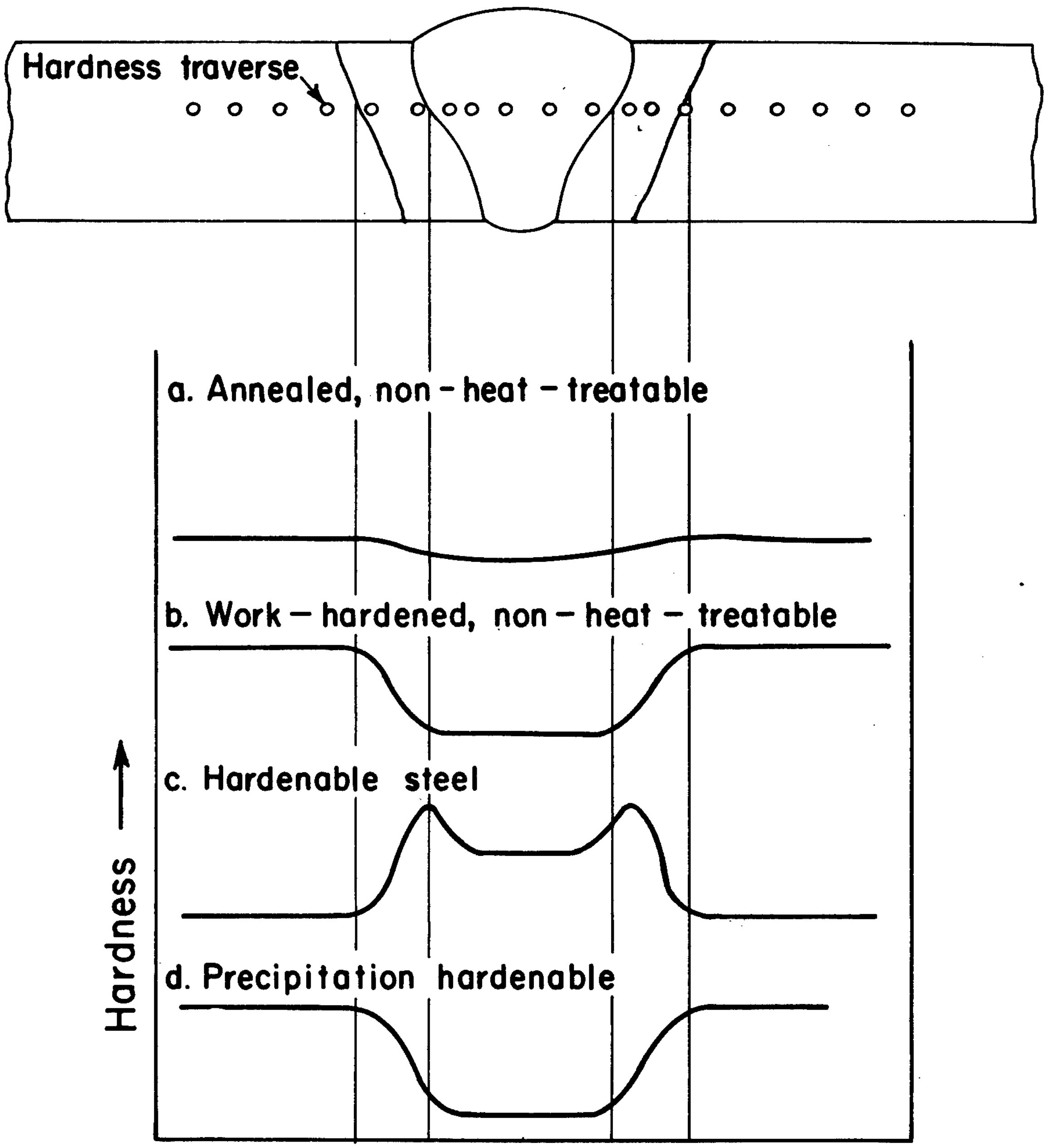


FIGURE 8. PATTERNS OF TYPICAL HARDNESS TRAVERSES ACROSS SINGLE-PASS WELDS IN FOUR BASIC TYPES OF MATERIALS

CHAPTER 3

ARC-WELDING POWER SUPPLIES

Section I. INTRODUCTION

39. GENERAL

a. The basic types of welding power supplies, their operation and use are discussed in this chapter. This chapter should be consulted for more detail when reference is made to a specific type of power supply in the next chapters on welding processes.

b. Arc-welding power supplies are made in a number of different designs and sizes to suit different welding methods and operations. In general, power supplies for arc welding are specialized pieces of equipment capable of delivering power over a wide range of current-voltage combinations.

c. A general idea of welding power supply ratings can be obtained from the fact that most arc welding operations require arc voltages ranging from about 15 to 30 volts and currents ranging from 50 to 350 amperes.

40. CLASSIFICATION

a. Power supplies for arc welding are classified by:

(1) Type of Welding Current. Welding power supplies are classified into two broad groups depending upon the type of welding current that they deliver to the arc. All power supplies are basically either ac or dc and differ only in their characteristics and in their methods of achieving suitable welding currents.

(2) Power Rating.

(a) All welding power supplies are normally rated as delivering a specified maximum current during a given duty cycle. The current level specified is generally the maximum average current that may be drawn from the power supply during the specified duty cycle without producing an excessive temperature buildup in the power supply.

(b) Unlike many other electric devices or machines that once turned on must deliver their rated output until shut off, a welding power supply, unless used on automatic processes, will be called on to deliver output during limited periods only. The welder must stop welding to change electrodes, adjust his work and his position. Thus a welding power supply is allowed to idle during part of its operating time. The duty cycle expresses, as a percentage, the portion of the time that the power supply can deliver its rated output in each of a number of successive 10-minute intervals. Thus, a 60% duty cycle (the standard industrial rating) means that the power supply can deliver its rated load output 6 minutes out of every 10 minutes. A 100% duty cycle power supply can produce its rated output continuously without exceeding the established temperature limits. An important point to remember is that the duty cycle is based on the output current and not on the power rating.

(c) Power supplies may be operated at higher than rated current on shorter duty cycles or at lower than rated current on longer duty cycles. For example, a power supply rated at 200 amperes and 60% duty cycle will safely operate at 250 amperes on a 38% duty cycle or at 155 amperes on a 100% duty cycle.

(3) Types of Power Conversion. Arc welding, as explained in Chapter 2, requires a low-voltage, high-current power source. Arc-welding power supplies generally convert some other form of energy or power into a form useful for arc welding. There are three methods of power conversion in common use: (1) transformers for a-c welding, (2) generators for a-c and d-c welding, and (3) rectifier types for d-c welding.

(4) Volt-Ampere Characteristics. Another common classification of welding power sources is constant current or constant potential (voltage). These will be discussed further in Section III of this chapter.

b. The balance of this chapter will be devoted to discussions of arc welding power supplies in terms of types of power conversion and the

volt-ampere characteristics of each type. The major uses and applications of each type will be discussed. For purposes of this discussion, manual welding will refer to processes in which the welding operator controls both travel and wire or electrode feed into the arc. Semiautomatic welding will refer to processes in which the welding operator controls the travel but the electrode is fed into the arc automatically. Automatic processes incorporate both automatic travel control and electrode feeding.

Section II. TYPES OF POWER CONVERSION

41. GENERAL

As noted earlier, a welding power supply serves to convert energy or power from some other source to electrical energy usable in the arc-welding process. The three methods of power conversion in common use are discussed below. The applications of each type of power supply are discussed in Section III of this chapter.

42. POWER CONVERSION METHODS

a. Transformer Type. Alternating-current power supplies usually are transformers that take the commercial a-c power from power lines and transform the voltage and current to values suitable for arc welding. The transformer also serves to isolate the weld circuit from the power lines.

b. Generator Types. A generator is used to convert mechanical energy into electrical power suitable for welding. The mechanical energy may be obtained from variety of sources, such as internal combustion engines and electric motors. The power output may be either ac or dc. The most familiar case of this type of power conversion is the d-c motor generator.

c. Rectifier Types. The rectifier-type power supplies rectify alternating current from a transformer or generator to produce direct currents. The most common rectifier types employ a transformer. The transformer-rectifier-type power supply is more compact than a d-c motor-generator and operates more efficiently and quietly, However, it does not have the flexibility or overload capacity of the motor-generator type.

d. Combination Types. Power supplies are produced which basically incorporate transformer and transformer-rectifier-type power supplies in a single cabinet. A simple switch allows the selection of either a-c or d-c welding power. This provides the welder with greater latitudes in choice of welding process.

Section III. VOLT-AMPERE CHARACTERISTICS

43. GENERAL

The power supply furnishes a controlled source of electrical power to the welding arc. For satisfactory welding, the power supply must be able to deliver the proper type and amount of electrical power for welding in measured and controlled amounts. The welding behavior of the arc and its response to changing welding conditions is largely dependent on the type of power supply and its proper adjustment for the type of welding.

44. STATIC VOLT-AMPERE CHARACTERISTICS

a. The static volt-ampere characteristics and the response time of a welding power source determine the welding characteristics. The static volt-ampere characteristics of a given welding power supply are best shown by characteristic curves. A typical set of characteristic curves for a power supply having both current and voltage control is shown in Figure 9. The solid lines represent various current tap settings, while the dotted lines represent various voltage tap settings. The curves are obtained by attaching a load across the output terminals of the welding power source and plotting voltage and current values for each tap setting as the load is varied.

45. DYNAMIC VOLT-AMPERE CHARACTERISTICS

a. Unlike the loads used for plotting the static volt-ampere characteristic curves, the welding load is dynamic. Large variations in arc voltage and welding current can occur over relatively short time periods. The dynamic response of the welding power supply to variations in arc voltage and welding current is determined by the current-rise time. The current-rise time is defined as the time required for the welding current to rise from no load to maximum short-circuit load conditions.

b. Short circuits occur in milliseconds and are therefore best recorded with the aid of an oscillograph. An oscillogram of the current

during a typical short circuit, such as might occur during arc starting or during short-circuiting metal transfer, is shown in Figure 10. The particular welding process and type of metal transfer will determine what the dynamic response of the power supply should be. For example, when welding in the short-circuiting metal transfer mode, the welding circuit might be modified to decrease the dynamic response of the power supply, i.e., increase the current rise time. This would reduce weld spatter because explosive vaporization of the electrode occurs when the current rise time is too fast.

c. By using nonconsumable electrodes, the static volt-ampere characteristics of an arc can also be studied. For a given arc length in a controlled atmosphere, the arc voltage will vary with arc current as shown in Figure 11a. As the arc current increases, the arc voltage required to maintain the arc decreases to a minimum and then increases slowly.

46. COMBINED EFFECT OF STATIC AND DYNAMIC CHARACTERISTICS

a. The establishment of an arc between an electrode and a plate is only possible if the characteristic curves of the power source and the arc intersect. Figure 11a shows the intersection of a typical arc curve with one of the characteristic curves of a typical drooping characteristic power source. The intersection point is commonly called the working point. An increase in arc length generally causes the arc characteristic curve to move toward higher voltage. The working point will follow the intersection of the two curves. When the arc length becomes too long, the situation shown in Figure 11b occurs, thus resulting in arc extinction.

b. One must remember that the static volt-ampere curves represent the arc and power supply under a given set of conditions. In reality, the arc is never static during welding. The arc length is constantly changing. The dynamic response of the welding power supply to variations in arc length along with the static characteristics of the power supply determine arc stability and weld quality to a large extent.

47. CONSTANT CURRENT POWER SUPPLIES

a. A constant current power supply is one that has characteristically "drooping" volt-ampere curves producing relatively constant current with a limited change in load voltage. Typical drooping volt-ampere curves are shown in Figure 9. This type of supply is conventionally used in conection with the manual welding processes and is available in both a-c and d-c.

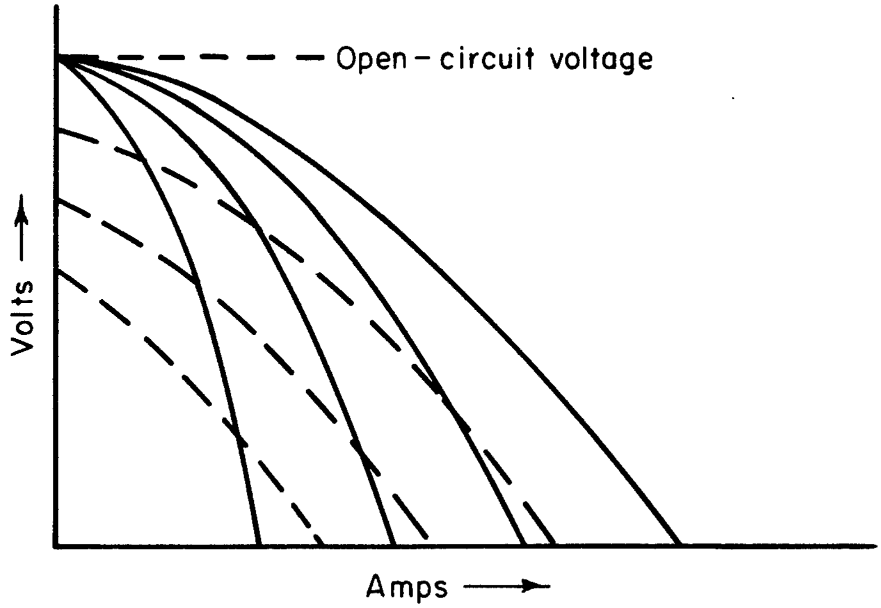


FIGURE 9. STATIC CHARACTERISTICS FOR A TYPICAL DROOPING VOLT-AMPERE WELDING POWER SUPPLY

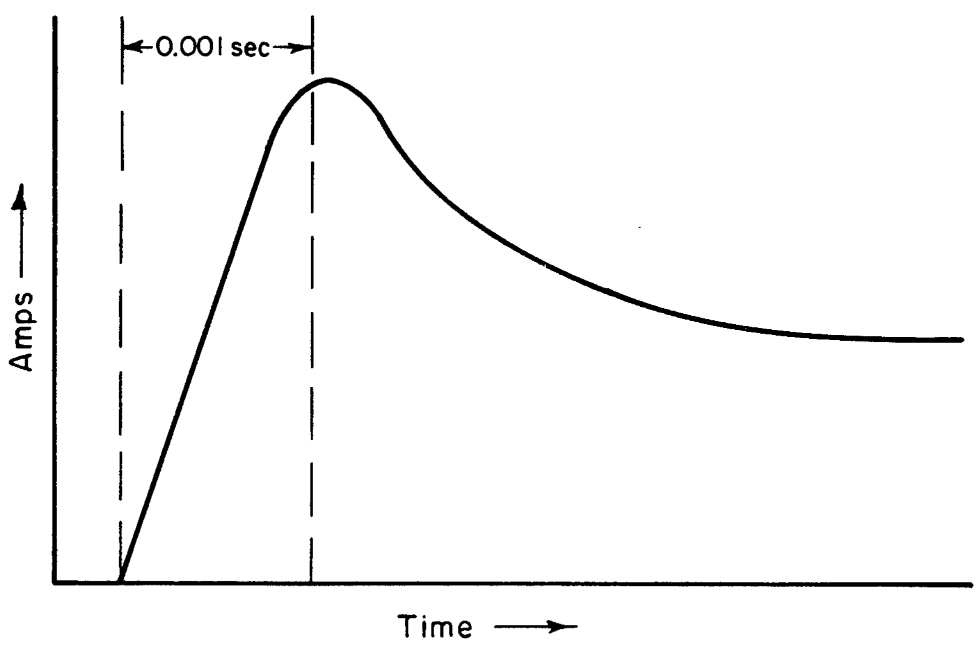


FIGURE 10. TYPICAL SHORT CIRCUIT SHOWING CURRENT RISE TIME FROM NO LOAD TO MAXIMUM LOAD

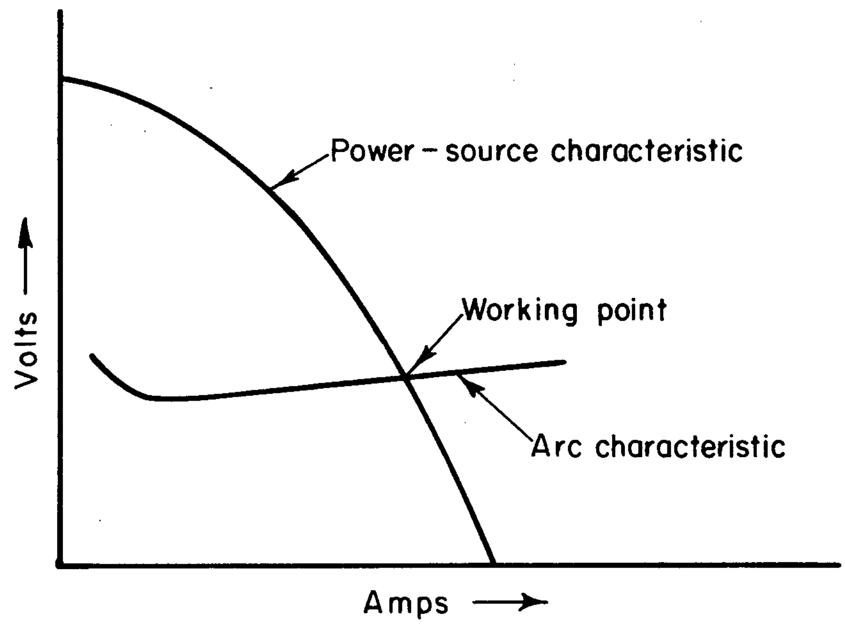


FIGURE 11a. TYPICAL VOLT-AMPERE CURVES FOR WELDING POWER SUPPLY AND FOR CONSTANT-ARC LENGTH ARC

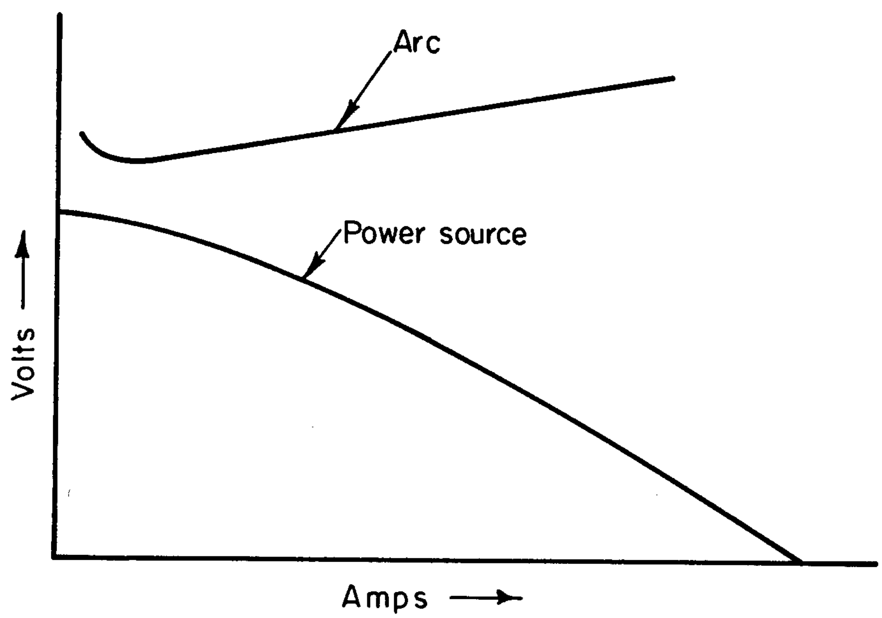


FIGURE 11b. ARC AND POWER-SUPPLY VOLT-AMPERE CHARACTERISTICS SHOWING SITUATIONS WHICH WILL LEAD TO ARC EXTINCTION

b. The large arc-length variations inherent in manual welding cause only minor variations in heat input when these power sources are used. The steep slope of the curves shown by the solid lines in Figure 9 allows very little variations in current for large variations in voltage. Thus, a fairly constant heat input is maintained during welding. The welder therefore has good control over weld penetration and arc stability.

c. For out-of-position welding where variations in heat input are desirable, the welder would select static volt-ampere characteristics similar to those shown by the dotted lines in Figure 9. With the somewhat flatter slope, the welder can control heat input by purposely varying arc length and thus varying the current.

d. Motor-generator power supplies generally have controls for the magnitude of both the open-circuit voltage and the short-circuit current. Transformer and transformer-rectifier types, however, generally have controls for the short-circuit current only. The motor-generator power supplies therefore provide somewhat greater versatility in slope selection for out-of-position welding.

e. Power supplies with drooping volt-ampere characteristics are not exclusively confined to manual processes. These power supplies can be used for semiautomatic and automatic operations where arc length is controlled by automatic changes in consumable-electrode feed rate.

f. Arc starting can sometimes be a problem with drooping arc-voltage power sources because of the limited short-circuit currents available. In manual welding, it is usually necessary to make contact between the electrode and the workpiece to start the arc. With some processes, high-voltage, high-frequency devices are used to initiate the arc so that the electrode does not have to touch the work. Many constant current power supplies are equipped with devices which provide current surges when short circuits occur as in arc starting and metal transfer.

g. Table III gives ratings of constant-current welding generators as standardized by the National Electrical Manufacturers Association (NEMA). It is possible to obtain increased current capacity by connecting generators in parallel. However, this should be done only by an experienced person following the manufacturer's specific instructions. This is because successful paralleling depends upon the output voltage, output setting, and polarity of each machine.

TABLE III. RATINGS OF CONSTANT-CURRENT d-c WELDING GENERATORS -- OUTPUT RATINGS[(a)] -- 60 PERCENT DUTY CYCLE AT RATED OUTPUT

Rates Amperes	at Load Volts	Minimum Amperes	at Load Volts	Maximum Amperes	at Load Volts
150	26	20	20	185	27
200	28	30	21	250	30
250	30	40	22	310	32
300	32	60	22	375	35
400	36	80	23	500	40
500	40	100	24	625	44
600	44	120	25	750	44

(a) The load voltages are based on the formula E = 20+0.04 I, where E is the load voltage and I is the load current. For currents above 600 amp the voltage shall remain constant at 44 volts.
Where the output current indicator is calibrated in amperes, the calibration points shall be based on the load voltages determined for each current setting by the formula E = 20+0.04 I, where E is the load voltage and I is the load current. For currents above 600 amp, the voltage shall remain constant at 44 volts.

48. CONSTANT ARC VOLTAGE (CONSTANT POTENTIAL)

a. Constant arc-voltage or constant-potential (CP) welding power supplies are available as d-c motor generators or transformer-rectifiers but not as a-c transformers. A constant-voltage arc-welding power supply is one which has characteristically flat volt-ampere curves producing relatively constant voltage with a change in load current. This type of power supply is conventionally used in connection with welding processes involving consumable electrodes fed at a constant rate. The burn-off rate of the welding electrode is automatically regulated by the arc to match the wire feed rate. This insures a constant arc length.

b. Most CP power supplies are equipped in some manner which permits the operator to adjust the slope of the characteristic volt-ampere curve from flat to rising or drooping. The control may have tap settings, or it may be infinitely variable. Typical volt-ampere characteristics for a CP power source are shown in Figure 12.

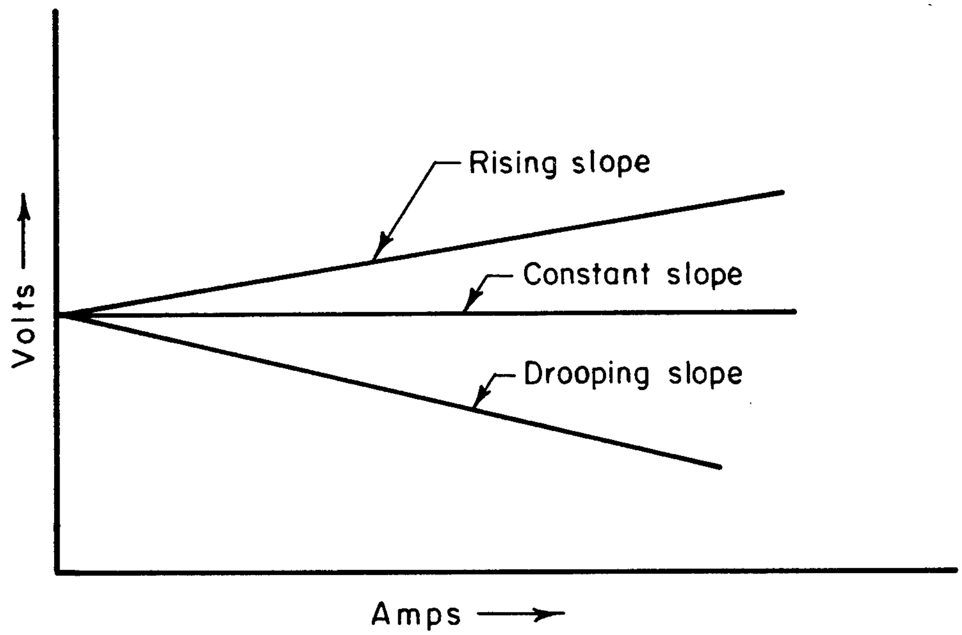


FIGURE 12. STATIC CHARACTERISTIC VOLT-AMPERE CURVES FOR A TYPICAL CP POWER SUPPLY WITH SLOPE CONTROL

c. Slope is important in controlling the short-circuit current. In some welding applications, the short-circuit current will be too high for smooth arc action when a flat or CP slope is used. The high short-circuit currents may create spatter and cause harsh starts. The use of a slightly drooping slope will limit short-circuit current and thus improve arc action. Many CP power supplies also have built-in reactors which can be used to control the rate of current buildup. This is important in short-circuiting metal transfer, as discussed in Paragraph 45b. The rising volt-ampere characteristic allows a greater variation in the wire feed rate in the semiautomatic and automatic processes than is possible with either of the other types without significantly changing the arc length.

Section IV. SPECIAL APPLICATIONS

49. GENERAL

Welding with d-c power provides more versatile control over the bead shape, penetration, and speed. Arc starting is much easier with direct current. Direct current is preferred: (1) where fast, accurate arc

starting is essential, (2) where close arc control is needed, and (3) where difficult contours are to be followed at maximum speeds. Alternating current minimizes arc blow. This assumes increasing importance at high welding currents.

50. MULTIPLE-ARC, SINGLE-POWER-SOURCE APPLICATIONS

a. Multiple Arc. Multiple arcs are used to increase electrode melting rates and to provide increased welding speed. Two arcs in close proximity (about 4 inches or less apart) are affected by each other's magnetic field. Two d-c arcs of like polarity flare together, whereas arcs of unlike polarity flare apart. Two a-c arcs allow considerable control over the amount and direction of arc deflection at each arc and permit maximum welding speed. Less control is obtained with the combination of d-c and a-c arcs, but the amount of control obtained is sufficient for many applications. When three arcs are used, the customary combination is d-c, a-c, a-c.

b. Two-Wire Parallel Power Techniques. The two-wire parallel power technique is an automatic welding process which employs two electrodes fed through the same welding head from one power source. This technique results in a very high deposition rate. The technique is used to gain speed on welds where fill-in is a major consideration, such as large, flat-position fillets, and wide vee joints. The two arcs pull together, causing back blow at the front arc and forward blow at the trailing arc. This relationship cannot be varied. This is the simplest form of multiple-wire welding and usually results in about a 50 percent increase in speed over a single arc.

c. Two-Wire Series Power Technique. The two-wire series power technique is used to obtain extremely high deposition rates with a minimum of penetration into the base metal. Each electrode in series arc welding operates independently, having its own feed motor and voltage control. The power-supply cable is connected to one welding head. The return power cable is connected to the second welding head instead of to the workpiece. The welding current travels from one electrode to the other through the weld puddle and surrounding material. The wires are usually positioned at an angle of 45 degrees to each other and at right angles to the direction of travel. The point of intersection of the center lines of the electrodes controls the penetration pattern of the weld bead. If the intersection point is too low, excessive penetration will result; if too high, inadequate fusion will result.

51. MULTIPLE-ARC, MULTIPLE-POWER-SOURCE APPLICATIONS

Multiple-arc, multiple-power-source applications (two or more electrodes each with a separately controlled power source) have a speed advantage on both fill-in welds and butt welds with a square-groove type of preparation. While multiple-power welding gives an increase in speed, the difficulty of setting the proper procedure on multiple separate arcs makes this process suitable mainly for long runs of identical joints. Multiple-arc, multiple-power-source operations call for a complicated procedure which takes into consideration the separate arcs and all the possible variations of current, spacing, electrode size, etc. When heavy plate is welded, at least one arc should be on alternating current. Two tandem arcs usually increase speeds at least 100 percent over the single arc. Three arcs may add another 50 percent.

52. STUD WELDING

Because stud welding demands more capacity, more consistency, and better control, special power sources have been designed especially for this process. Stud welding calls for high-energy outputs over relatively short time periods. Power sources of various types capable of producing high-energy outputs over short duty cycles have been developed for stud-welding applications.

Section V. SAFETY

53. GENERAL

A welding machine should be treated with the same regard for safety that any electrical device would be. Most of the precautions that should be taken are obvious, but still bear repeating. The nameplates of all devices should be checked carefully and compared to the known line power available. When a considerable number of units are being installed, unbalanced line loads can be minimized by connecting them to different phases. However, in this case, welders should avoid physical contact with one another when working on a single large weldment as a voltage will exist between electrode holders.

54. INSTALLATION OF THE POWER SUPPLY

When adapting a unit for specific voltage, the instruction manual for the specified power supply should be consulted to make sure that all change-overs for the specific line voltage have been completed. Installation of

the power supply should be done by a licensed electrician. Part of the installation should be a fusible safety switch, mounted on the wall near the power supply. The case of the unit should always be grounded. Special care should always be taken to assure tight connections on the output side of the power supply.

55. EQUIPMENT LOADING

Care should be taken in applying arc-welding equipment to insure that the current rating chosen is adequate to handle the job. Welding machines should not be operated above their current ratings and corresponding rated duty cycles listed in the standards or above the limits specified by the manufacturer. Consideration should be given to the fact that actual welding currents may be higher than shown by indicators on the machines if welding is done with short leads or low arc voltages. Welding cables should be of the extra-flexible type designed especially for welding and of size adequate for current and duty cycles reasonably expected.

56. ELECTRIC SHOCK

Avoidance of electric shock is largely within the control of the welding operator. Therefore, it is especially important that he be thoroughly instructed how to avoid shock. Voltages required for arc welding are low and normally will not cause injury or severe shock. The fact that they are low may, and does, lead to carelessness. These voltages are nevertheless sufficiently high that under some circumstances they may be dangerous to life. Severity of shock is determined largely by the amount of current flowing through the body and this is determined by voltage and contact resistance of the area of skin involved.

CHAPTER 4.

SHIELDED-METAL-ARC WELDING

Section I. INTRODUCTION

57. DEFINITION

a. Shielded-metal-arc welding is an arc-welding process wherein coalescence is produced by heating with an electric arc between a covered metal electrode and the work. Shielding is obtained from decomposition of the electrode covering. Pressure is not used and filler metal is obtained from the electrode.

b. In practice, the process is limited primarily to manual-covered electrodes in which the welding operator manipulates the electrode. Automatic-feed apparatus is available for use with covered electrodes, and these find some use for fillet welding structures. Nevertheless, the shielded-metal-arc process can be considered primarily a manual welding operation.

58. IMPORTANCE AND USES

a. The shielded-metal-arc process can be used for welding most of the common engineering alloys. It is used most extensively for joining various types of steels. These include low-carbon or mild steels; low-alloy, heat-treatable steels; and high-alloy steels, such as stainless steels. It is also used extensively for joining common nickel alloys and to a lesser extent for copper and aluminum alloys.

b. Until quite recently, shielded metal-arc was the only all-position process available. It was also best for weldments in the flat position where it was either impractical or uneconomical to set up equipment to position the work for automatic welding. Presently, covered electrodes represent a very large proportion of total electrodes sales in this country. (In 1963, approximately 650 million pounds of ferrous electrodes were sold.) The percentage of covered electrode sales may diminish in the future, however, in light of recent developments in semiautomatic and automatic welding processes suitable for out-of-position work, and in an improved semiautomatic process for flat-position work.

59. EQUIPMENT

a. The power supplies used for arc welding have been discussed in detail in Chapter 3.

b. In addition to a source of welding power (a-c transformer, d-c generator, a-c generator, or d-c rectifier), the following equipment is used: (1) welding machine accessories such as oscillators, voltage-protective devices, crater eliminators, remote control devices, generator or motor idling devices, and resistor banks, and (2) auxiliary equipment such as cables, cable connectors, electrode holders, ground connectors, helmets, hand shields, protective clothing, chipping and slag-removal hammers, weld gages, and brushes.

Section II. PRINCIPLES OF OPERATION

60. GENERAL

Basically, the shielded metal-arc process consists of establishing an electric arc between a metallic electrode and the workpiece to be welded. The arc develops intense heat, which melts the metal of the workpiece and forms a molten pool. At the same time, the electrode tip melts and is carried across the arc into the molten pool. The usual current range for manual operation is from 15 to 500 amperes. The voltage across the arc varies from 14 to 24 volts with bare or lightly covered electrodes and from 20 to 40 volts with the covered electrodes.

61. METAL TRANSFER

Most of the melted electrode metal is transferred to the work. However, some of the metal is thrown free of the weld as spatter and some is vaporized. Even the vaporized metal is partially condensed in the molten pool, which is at a much lower temperature than the electrode tip. The remainder of the vaporized metal escapes into the surrounding air, becomes oxidized, and appears as smoke or fumes.

62. COATING FUNCTIONS

The materials covering the electrodes for shielded metal-arc welding perform various functions when heated or otherwise broken down by the arc. They (1) produce a gas which shields the arc from the atmosphere, (2) promote electrical conduction across the arc and help stabilize it,

(3) add slag-forming materials to the molten weld pool for the purpose of refining the molten metal and, in some cases, of adding alloying elements, and (4) provide materials for the purpose of controlling bead shape. The process is shown schematically in Figure 13.

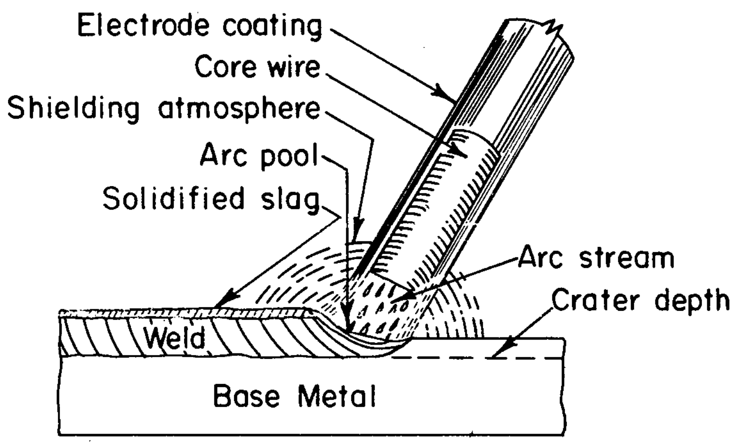


FIGURE 13. SCHEMATIC REPRESENTATION OF THE SHIELDED METAL-ARC WELDING PROCESS

63. ARC ENERGY

The melting rate in the arc zone is directly related to the electrical energy supplied to the arc. Part of this energy is used to melt the base material and part is used to melt the electrode core wire and covering. The electrical polarity and the electrode covering constituents determine the balance of energy. Where the arc energy is more associated with base material, penetration is deeper; where the arc energy is more associated with electrode, the burnoff rate of the electrode is greater.

64. CURRENT

The melting rate is directly affected by the magnitude of the current. This is shown in Figure 14. It is less affected by the arc voltage. As the current increases, the current density at the electrode tip also increases, thus increasing the energy available for melting. Preheating of the electrode increases with the square of the current. Therefore, small increases in current cause large increases in electrode preheat and further increases the melting rate.

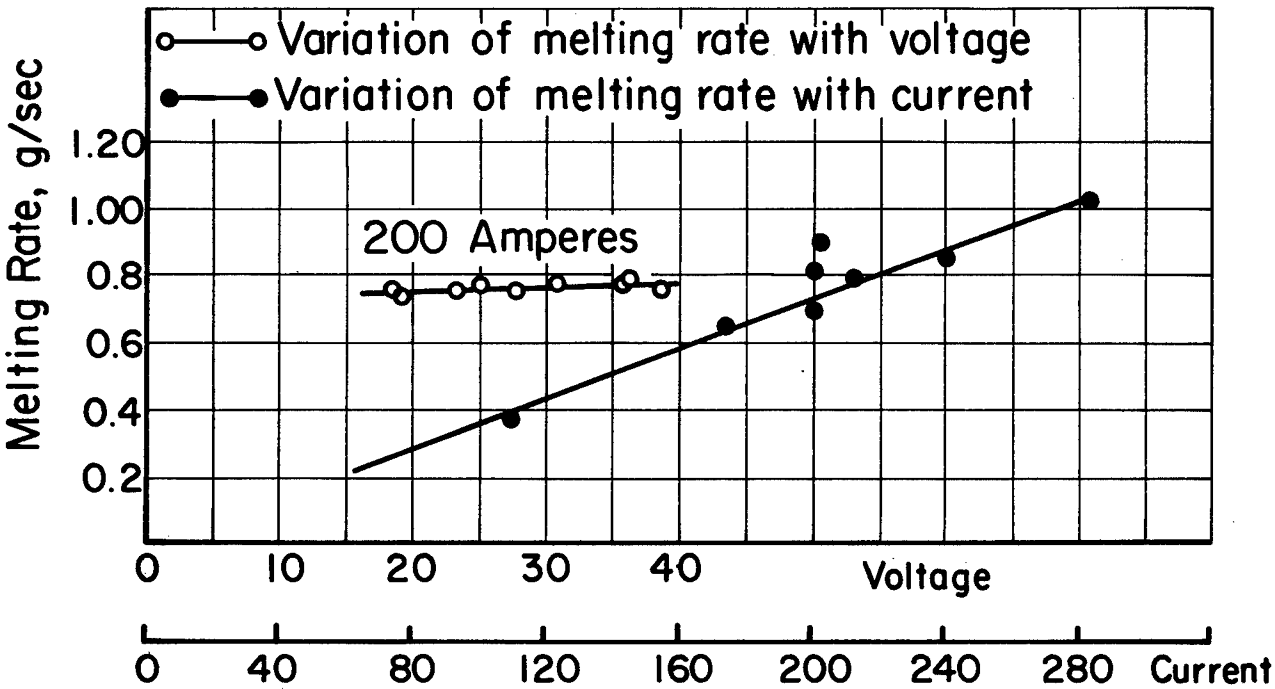


FIGURE 14. EFFECT OF CURRENT AND VOLTAGE ON ELECTRODE MELTING RATE IN SHIELDED METAL-ARC WELDING

65. PINCH EFFECT

As the end of the electrode is heated by the effects of energy concentration and resistance, it becomes plastic. Concentric magnetic forces around the electrode then tend to pinch off globules of metal, which are transferred across the arc. It is in this manner that the largest percentage of weld metal is deposited. Because these large globules tend to cause short circuits, the characteristics of the welding power supply are important. A power supply with excessive short-circuit current would tend to blast the globule and cause unnecessary spatter, as discussed in Chapter 3.

66. ARC STABILITY

a. Arc stability refers to the tendency of the arc to burn steadily in spite of continually changing conditions during the course of welding. The important factors influencing arc stability are: (1) open-circuit and transient voltage recovery characteristics of the welding machine, (2) the

drop transfer, and (3) the degree of ionization of the arc stream characteristic of the electrode.

b. Open-circuit voltage affects the re-establishment of the arc after each instantaneous short circuit encountered when a molten metal globule transfers across the arc. The magnitude of the voltage, as well as the speed with which it rises, affects the re-establishment of the arc. As the short circuit is cleared, the full open-circuit voltage should be available nearly instantaneously to re-establish the arc. The time constant for the rise to open-circuit voltage in d-c welding is incorporated into the design of the machine.

c. In a-c welding, both current and voltage reverse polarity the same number of cycles as the frequency of the line input to the welding power supply. The current and voltage would be turned off each time they changed direction, or 120 times a second for a 60-cycle source. Since this would cause unstable welding conditions, a series reactor is used to cause a phase shift between the current and voltage waves. Thus, as the current goes through zero, the arc is extinguished, but, because of the phase difference, there is a voltage present which immediately establishes current flow in the opposite direction.

d. In manual welding, it is impossible for the welder to hold a constant arc length. Varying arc lengths cause arc voltage to vary, which in turn produces a change in welding current. The greater the slope of the volt-ampere curve within the welding range, the smaller the current change for a given voltage change. It is desirable, in many welding operations, to maintain a constant current in order to obtain a maximum welding speed and quality. In such cases, therefore, a steep volt-ampere characteristic is desirable. In other cases, a flat volt-ampere characteristic is desirable to enable the welder to control welding current within limits by varying arc length and thereby varying arc voltage.

e. The open-circuit voltage should be considerably higher than the nominal operating arc voltage. Ordinarily, the open-circuit voltage is not high enough to establish the arc automatically. The arc must be struck by touching the electrode to the work and then withdrawing it. If this short-circuit time is appreciably long, the arc may be established from short-circuit conditions due to localized electrode melting.

67. ARC BLOW

a. Arc blow is a phenomenon encountered principally in direct-current welding. It may occur to a lesser degree when welding with alternating current under certain conditions. It occurs primarily when welding ferromagnetic materials such as steel but may also be encountered when welding nonmagnetic materials held in a magnetic fixture. Direct current flowing through the electrode and plate sets up magnetic fields around the electrode. These fields react with the fields around the electrode and tend to deflect the arc from its intended path. The arc is usually deflected either forward or backward in the direction of travel, but may be deflected to the side. The condition results in incomplete fusion and excessive weld spatter and can become so severe that a satisfactory weld cannot be made.

b. This arc deflection, in either direction, is caused by the effects of an unbalanced magnetic field. A conductor, carrying current, produces circular magnetic fields around the conductor in planes perpendicular to the conductor as shown in Figure 15. In welding, this magnetic field is superimposed on the steel and across the gap to be welded. Unequal field concentrations across the gap or around the arc will cause the arc to bend away from the heavier concentration. The field is conducted by the steel more readily than by air, so it tends to remain within the boundaries of the steel plates. Thus, when the electrode is near either end of the weld as shown in Figure 16a, the field around the electrode must crowd across the gap between the electrode and the end of the plate. This causes a high field concentration on one side of the arc at the start and finish of the weld and tends to make the arc blow away from the ends of the plates - a forward blow at the beginning and a back blow at the finish. The forward blow is only momentary since the deposited metal and the electrode travel provide an easier path for the field. For the rest of the weld, a slight back blow is created. This is because the field behind the arc is in the plate and weld, leaving the field in front as it crosses the gap as the main influence on the arc. This back blow becomes very severe at the end of the weld as the field ahead of the electrode becomes more crowded.

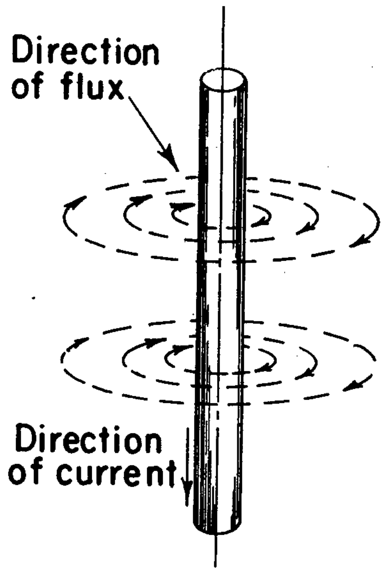


FIGURE 15. MAGNETIC FIELDS AROUND AN ELECTRIC CONDUCTOR

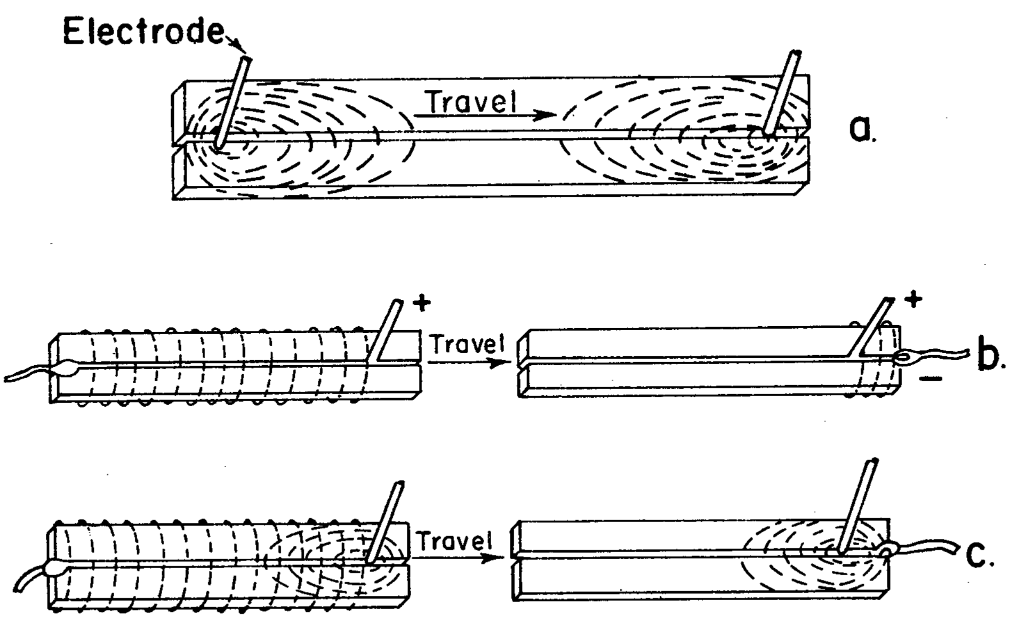


FIGURE 16. MAGNETIC FIELDS AT START AND END OF WELD

c. The welding current passing through the work also causes the base metal to act as a conductor with a magnetic field around it. The circular fields are in planes perpendicular to the work around the current path between the electrode and the point at which the work is grounded as shown in Figure 16b. This "ground effect" is most apparent on narrow material, and becomes less noticeable as the base material becomes wider.

d. In reality, the two magnetic fields mentioned above are one continuous series of circles perpendicular to the current path, which includes the ground cable, the work, and the electrode. However, for ease of illustration, the magnetic fields around the electrode and work are diagrammed as two separate fields superimposed on each other, as shown in Figure 16c.

e. Unless the arc blow is unusually severe, corrective steps will counteract the conditions causing the arc blow. All or some of the following corrective steps may be necessary:

(1) If the machine being used is of the type producing both alternating and direct current, switch to alternating current. Alternating current prevents the formation of strong magnetic fields.

(2) Current may be reduced.

(3) Weld toward a heavy tack or toward a weld already made.

(4) Use back stepping on long welds.

(5) Place ground connections as far as possible from joints to be welded.

(6) If back blow is the problem, place the ground connection at the start of the weld.

(7) If forward blow causes trouble, place the ground connection at the finish of the weld.

(8) Wrap the ground or lead cable around the workpiece and pass ground current through it in such a direction that a magnetic field will be set up to neutralize the blow.

(9) Hold as short an arc as possible to help the arc force counteract the arc blow.

(10) Point the electrode so that the arc force counteracts the arc blow.

Section III. WELDING ELECTRODES

68. ELECTRODE COVERINGS

a. Electrodes are commercially manufactured in diameters ranging from 1/16 to 3/8 inch and usually in lengths of 9 to 18 inches. The selection of proper electrode size depends primarily on the thickness of the work and the welding position. The composition of the electrode depends primarily on the composition of the metals to be welded and the strength requirements of the weld.

b. Among the several types of electrodes which have been used in the past, or are now in common use, are dust or drawn finish, lightly covered, and heavily covered electrodes. Heavily covered electrodes are now most commonly used. These make use of all the benefits of chemical coverings. The heavy coverings vary from 10 to 55 percent of the total electrode weight. They make possible the control of the arc characteristics and of the physical and chemical properties of the deposited metal. During welding, the covering extends beyond the metal core and serves to direct and concentrate the arc stream, to reduce thermal losses and to increase the temperature of the electrode tip.

c. In the heat of the arc, the heavy covering gives off large quantities of gas which envelop and shield the arc and metal from the surrounding atmosphere. This gaseous envelope is produced by the combustion of the organic materials and the volatilization of other covering ingredients. The gases shield the arc by excluding air and consuming oxygen. If combustion materials are not used in the covering, the arc is shielded by vaporized metallic oxides and silicates.

d. The action of the arc on the covering results in a slag formation which floats on top of the molten weld metal and insulates it against the air during cooling. The slag is produced by the melting and reaction of the less volatile mineral ingredients of the covering and may easily be removed after the weld metal is cooled. This molten slag removes oxides and other impurities from the weld. It also increases the fluidity of the metal and causes it to flow more smoothly and uniformly.

e. Electrode coverings are very poor conductors of electricity. This permits covered electrodes to be used in very close quarters, since contact with the work will not cause short circuiting.

f. The covering can be used to introduce alloying elements to the weld metal and increase tensile strength, hardness, corrosion resistance, and other physical properties.

g. Electrode coverings are usually applied by one of the following methods: (1) extrusion of a doughlike consistency of flux onto the core wire, or (2) single or multiple dip of the core wire into flux paste. Subsequent drying or baking of the electrode is necessary to eliminate moisture from the flux.

69. ELECTRODE IDENTIFICATION

A system of color identification for arc-welding electrodes, set up by the National Electric Manufacturers Association (NEMA) and the American Welding Society (AWS), has been used in the past to identify covered electrodes. Although it is still used to a minor extent, the system is being changed and therefore will not be discussed in this volume. The new system being adopted consists of printing the classification number of the wire, as shown in Figure 17.

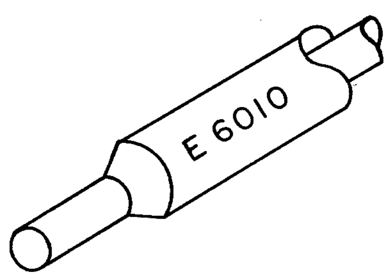


FIGURE 17. NATIONAL ELECTRIC MANUFACTURERS ASSOCIATION IDENTIFICATION BY STAMPING AWS CLASSIFICATION ON ELECTRODE COVERING

70. MILD-STEEL ELECTRODES

a. Electrodes have been numerically classified by the American Welding Society and the American Society for Testing and Materials. The

same numerical identification is used by government specifications. Mild-steel electrodes are classified in terms of mechanical properties, low-alloy electrodes by mechanical properties and chemical analysis, and most others by chemical analysis.

b. The prefix "E" in the classification number indicates a metallic arc-welding electrode which is consumed as filler metal. The next two numbers, either "60" or "70", originally showed the minimum tensile strength in the stress-relieved condition. They now also indicate ultimate strengths in the as-welded condition. This is shown in Table IV.

c. The third digit suggests welding positions for which the electrode might be used. The number "1" indicates all positions, although vertical and overhead welding are usually restricted to a maximum electrode diameter of 3/16 inch (5/32 inch for EXX15, EXX16, and EXX18). Electrodes for horizontal fillet and flat position welding are indicated by "2", and those for flat position only have the numeral "3" for the third digit.

d. The fourth digit indicates coating design, but, in the case of 0's, must be used in conjunction with the third digit. E6010 electrodes have high-cellulose sodium coatings, while E6020 and E6030 have high iron oxide coatings. A fourth digit "1" indicates high-cellulose potassium; "2", high-titania sodium powder; "3", high-titania potassium; "4", high-titania iron powder; "5", low-hydrogen sodium; "6", low-hydrogen potassium; and "8", low-hydrogen iron powder.

e. The principal tests used for selecting mild steel electrodes are operating characteristics and mechanical properties. These are summarized for a number of electrodes in Tables V and VI.

71. LOW HYDROGEN ELECTRODES

a. Low-hydrogen electrodes include EXX15, EXX16, EXX18, and EXX28. These electrodes have coatings low in hydrogen forming compounds so only traces of hydrogen or moisture are present in the arc atmosphere. They form a carbon dioxide shield around the arc due to decomposition of calcium carbonate in the coating. The coatings of these electrodes are slightly thicker (10 to 15 percent) than the coatings used for normal electrode types such as E6010 or E6012 types.

b. Low-hydrogen electrodes are baked at high temperatures and packaged in moisture-proof containers so that absolute moisture in the covering should be less than 0.2 percent. However, they will easily reabsorb moisture if exposed to high humidity.

TABLE IV. MECHANICAL PROPERTIES OF MILD- AND LOW-ALLOY STEEL WELD METAL (AS-WELDED)

AWS-ASTM Classification	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 in., percent	Reduction of Area, percent	Charpy Keyhole, ft-lb		Charpy V-Notch, ft-lb	
					70 F	-40 F	70 F	-40 F
E6010	60 to 68	48 to 58	22 to 28	35 to 60	30 to 40	15 to 25	50 to 80	10 to 25
E6011	60 to 70	48 to 61	22 to 30	35 to 60	30 to 40	15 to 25	50 to 80	10 to 25
E6012	60 to 78	48 to 65	17 to 22	20 to 40	20 to 30	5 to 15	25 to 55	2 to 10
E6013	60 to 78	48 to 65	17 to 22	25 to 50	25 to 35	5 to 20	30 to 60	5 to 15
E6020 and E6030	60 to 68	48 to 58	25 to 30	40 to 60	25 to 35	15 to 25	40 to 70	10 to 25
E6027	60 to 68	48 to 55	25 to 30	40 to 60	25 to 35	15 to 25	40 to 70	10 to 25
E6014 E7014	60 to 72 70 to 85	48 to 60 58 to 77	17 to 25	30 to 50	25 to 35	15 to 25	40 to 70	10 to 25
E6015 and E6016 E7015 and E7016	60 to 72 70 to 76	48 to 60 58 to 62	22 to 35	55 to 75	35 to 50	25 to 40	70 to 100	25 to 40
E6018 E7018	60 to 72 70 to 85	48 to 60 58 to 70	22 to 30	55 to 75	35 to 50	25 to 40	70 to 100	25 to 40
E6024 E7024	60 to 72 70 to 85	48 to 60 58 to 75	17 to 22	20 to 40	25 to 35	10 to 20	30 to 60	5 to 20
E6028 E7028	60 to 72 70 to 85	48 to 60 58 to 74	22 to 30	55 to 75	35 to 50	25 to 40	70 to 100	15 to 40

TABLE V. OPERATING CHARACTERISTICS OF MILD-STEEL AND LOW-ALLOY STEEL ELECTRODES

Classification	Current and Polarity	Welding Positions	Type of Covering	Penetration	Surface Appearance	Slag
EXX10	D-C reverse polarity (electrode positive)	All	High-cellulose sodium	Deep	Flat, wavy	Thin
EXX11	A-C or D-C reverse polarity (electrode positive)	All	High-cellulose potassium	Deep	Flat, wavy	Thin
E6012	A-C or D-C straight polarity (electrode negative)	All	High-titania sodium	Medium	Convex, rippled	Heavy
EXX13	A-C or D-C straight polarity (electrode negative)	All	High-titania potassium	Shallow	Flat or concave, slight ripple	Medium
EXX14	D-C either polarity	All	Iron powder, titania	Medium	Smooth, fine ripples	Medium
EXX15	D-C reverse polarity (electrode positive)	All	Low-hydrogen sodium	Medium	Flat, wavy	Medium
EXX16	A-C or D-C reverse polarity (electrode positive)	All	Low-hydrogen potassium	Medium	Flat, wavy	Medium
EXX18	A-C or D-C reverse polarity (electrode positive)	All	Iron powder, low hydrogen	Medium	Convex, smooth even ripple	Medium
EXX20	D-C straight polarity (electrode negative) or A-C for H-fillets; D-C either polarity or A-C for flat position welding	H-fillets and flat	High iron oxide	Medium	Flat or concave, smooth	Heavy
EXX24	A-C or D-C either polarity	H-fillets and flat	Iron powder, titania	Shallow	Convex, smooth fine ripple	Medium
EXX27	D-C straight polarity (electrode negative) or A-C for horizontal fillet welds and D-C either polarity or A-C for flat position	H-fillets and flat	Iron powder, iron oxide	Medium	Slightly concave, smooth, even ripple	Heavy
EXX28	A-C or D-C reverse polarity (electrode positive)	H-fillets and flat	Iron powder, low hydrogen	Shallow	Flat to concave, smooth, fine ripple	Heavy
EXX30	D-C either polarity or A-C	Flat only	High iron oxide	Shallow	Flat, smooth	Heavy

TABLE VI. TENSILE-STRENGTH AND DUCTILITY REQUIREMENTS[a] FOR STRESS-RELIEVED ALL-WELD METAL TENSION TEST SPECIMENS

AWS-ASTM Classification Number	Tension Strength, psi	Yield Point, psi	Elongation in 2 In., %
E7010, E7011, E7015, E7016	70,000	57,000	22
E7020	70,000	57,000	25
E8010, E8011, E8015, E8016, E8018	80,000	67,000	19
E8013	80,000	67,000	16
E9010, E9011, E9015, E9016, E9018	90,000	77,000	17
E9013	90,000	77,000	14
E10010, E10011, E10015, E10016, E10018	100,000	87,000	16
E10013	100,000	87,000	13
E11015, E11016, E11018	110,000	97,000	15
E12015, E12016, E12018	120,000	107,000	14

(a) Minimum.

c. It is possible to add such alloying elements as carbon, manganese, silicon, chromium, nickel, molybdenum, vanadium, etc. to the coverings. With such electrodes heat-treatable deposits ranging from 70,000 to approximately 300,000 psi can be obtained. This makes it possible to produce weld metal matching heat-treating characteristics of specific steels.

d. Low-hydrogen electrodes were developed to eliminate "underbead cracking" when welding hardenable, high-tensile, high-carbon alloy steels. These cracks are caused by absorption of hydrogen into the weld metal and occur in the base metal just under the weld metal. The hydrogen migrates through the weld metal and collects in the highly strained martensitic area of the base metal, causing cracking. Such cracks may occur whenever ordinary electrodes are used for welding high-tensile steels. Eliminating hydrogen allows the welding of "difficult-to weld" steels with less preheat, thus improving welding conditions.

e. Penetration is not as deep with low-hydrogen electrodes as with some others, such as E6010, but is sufficient for most welding jobs.

f. Weld metal deposited with low-hydrogen electrodes is superior in as-welded mechanical properties to that deposited with conventional electrodes such as E6010 and E6020. Tensile strengths of better than 120,000 psi with elongations of over 20 percent can be readily obtained. Some of the heat-treatable deposits will go as high as 300,000 psi. One of the outstanding qualities of these electrodes is their low-temperature-impact properties.

72. IRON-POWDER ELECTRODES FOR MILD STEEL

a. The addition of iron powder to electrode coverings was introduced in 1953 and has gained widespread acceptance. Over 10 percent of all the mild-steel-electrode tonnage consumed is now of this type.

b. As the electrode melts, the iron powder and the core wire are deposited in the weld metal. Since much of the electrical energy is used to melt the iron powder, higher welding currents can be used. This results in a higher deposition rate than for conventional electrodes. These electrodes can be used in a "drag" technique, where the electrode is in contact with the work. This forms a deep-arc cup and permits a more open-arc technique to be used for groove welds and out-of-position welding.

73. LOW-ALLOY, HIGH-STRENGTH ELECTRODES

a. The expanding use of alloy constructional steels has resulted in the development of many low-alloy, high-strength electrodes. Low-alloy, high-strength steel electrodes are available with many different types of coatings and with strengths greater than 120,000 psi. In some cases, weld deposit chemistries match the base metals; in others, they vary considerably.

b. The electrodes are classified by a combined specification of mechanical properties and chemical composition. Table V shows the AWS-ASTM classifications with tensile strength, yield strength, and ductility. Chemical requirements for low-alloy electrodes are shown as a suffix to the classification number. Table VII shows the more popular analysis designations.

74. CORROSION-RESISTANT CHROMIUM AND CHROMIUM-NICKEL FILLER METALS

a. Corrosion-resistant chromium and chromium-nickel filler metals are those which deposit ferrous weld metal containing more than 4 percent chromium and less than 50 percent nickel. Because of the corrosion and heat-resistant properties of these alloys, they are frequently referred to as the stainless electrode series.

b. The classification of stainless steel-covered electrodes includes a prefix "E", per AWS-ASTM or MIL per military specification, designating electrodes for manual shielded-metal-arc welding. The three digits following this prefix indicate the chemical composition of the filler metal.

c. The classification also involves the use of suffixes. The suffixes L and ELC indicate extra-low carbon content for military and commercial specifications respectively. The suffix HC indicates extra-high carbon content. Two other suffixes, Cb for columbium and Mo for molybdenum, are used to fill in the gaps in the American Iron and Steel Institute (AISI) numbers. Stainless filler metals and their chemical analyses are shown in Table VIII.

d. Two usability classifications, shown in Table IX, are defined, each designated by a two-digit number following the composition designation (e.g., E308-15).

TABLE VII. SIMPLIFIED CHEMICAL REQUIREMENTS FOR LOW-ALLOY STEEL COVERED ELECTRODES

Chemical Group	AWS-ASTM Classification Number	Manganese, %	Chromium, %	Molybdenum, %	Nickel, %	Vanadium, %
Carbon-molybdenum steel electrodes	E70XX-A1			0.40-0.65		
Chromium-molybdenum steel electrodes	E80XX-B1		0.40-0.65	0.40-0.65		
	E70XX-B2 E80XX-B2		1.00-1.50	0.40-0.65		
	E80XX-B3 E90XX-B3		2.00-2.50	0.90-1.20		
	E80XX-B4		1.75-2.25	0.40-0.65		
Nickel steel electrodes	E80XX-C1				2.00-2.75	
	E80XX-C2				3.00-3.75	
	E80XX-C3				0.80-1.10	
Manganese-molybdenum steel electrodes	E90XX-D1	1.25-1.75		0.25-0.45		
	E100XX-D2	1.65-2.00		0.25-0.45		
All other low-alloy	EXXXX-G	1.00 min[a]	0.30 min[a]	0.20 min[a]	0.50 min[a]	0.10 min[a]

(a) Any one of these elements in amounts above the specified minimum is considered proof of deliberate alloy additions to produce a low-alloy steel electrode.

TABLE VIII. NOMINAL CHEMICAL COMPOSITION OF STAINLESS STEEL ELECTRODES

AWS-ASTM Classification Number	Nominal Composition, percent				
	Carbon	Chromium	Nickel	Molybdenum	Columbium plus Tantalum
E308	0.08 max	19	9		
E308ELC	0.04 max	19	9		
E309	0.15 max	25	12		
E309Cb	0.12	25	12		0.7-1.0
E309Mo	0.12	25	12	2-3	
E310	0.20 max	25	20		
E310Cb	0.12	25	20		0.7-1.0
E310Mo	0.12	25	20	2-3	
E312	0.15	29	9		
E316	0.08 max	18	12	2-2.5	
E316ELC	0.04 max	18	12	2-2.5	
E317	0.08	18	12	3-4	
E318	0.08	18	12	2-2.5	6xC min to 0.80 max
E330	0.25 max	15	35		
E347	0.08	20	10		10xC min to 1.00 max
E410	0.12 max	12			
E430	0.10 max	16			
E502	0.10 max	5		0.45-0.65	

TABLE IX. USABLE POSITIONS AND TYPES OF CURRENT FOR CHROMIUM AND CHROMIUM-NICKEL ELECTRODES

Usability Designation	Direct Current		Alternating Current	
	Flat and Horizontal Fillet	Vertical and Overhead	Flat and Horizontal Fillet	Vertical and Overhead
-15	All sizes	3/32 in. and smaller	Not recommended	Not recommended
-16	All sizes	5/32 in. and smaller	All sizes	5/32 in. and smaller

e. The terms "lime", "lime-titania", and "titania" are frequently used to designate various types of coverings for stainless electrodes. In general, a lime-type covering is one whose mineral ingredients comprise chiefly limestone and fluorspar with minor amounts (up to about 8 percent) of titanium dioxide. Coverings containing more than 20 percent titanium dioxide are usually considered as the titania type, and those containing between 8 and 20 percent are considered to be the lime-titania type.

(1) The basic lime-type covering is usually applicable for electrodes operating on dc, reverse polarity only. In the flat position, the bead ripples are less uniformly spaced and the fillet weld contours are more convex than with the titania type. In the vertical position, this type of electrode is usually preferred because smooth, uniform welds can be made easily. Fully austenitic chromium-nickel welds from lime-type electrodes show considerably less tendency to crack or fissure than those from titania-type electrodes. The -15 classification is usually applicable to lime-type covered electrodes.

(2) For a-c welding, the covering always contains some titania, usually sufficient to classify it as a titania type. In addition, readily ionizing elements such as potassium are added for arc stability. Such electrodes are designated a-c/d-c electrodes, and although adjusted to make them usable with a-c, they are more frequently used with d-c, reverse polarity. They are used in preference to the lime-type electrodes for flat-position welding, particularly for smooth concave fillet

welds or butt welds which require finish grinding, because of the ease with which the welder can deposit uniform metal with a minimum of reinforcement. If they qualify as an all-position electrode, they may be designated -16. Titania-type electrodes are also available for d-c, reverse polarity only.

(3) The lime-titanium covering is more often applied to the straight chromium or chromium-molybdenum steels than to the chromium-nickel steels. Depending on the remaining ingredients, electrodes with this type of covering may be used with d-c only, or on both a-c and d-c; they are all-position electrodes.

f. Mechanical properties of chromium and chromium-nickel weld metal are shown in Table X.

75. NICKEL AND HIGH-NICKEL-ALLOY FILLER METALS

a. Filler metals containing significant amounts of nickel fall into many categories. In this section we will consider only those with 50 percent or more of nickel.

b. The system of classification of these filler metals is shown in Figure 18. The prefix "MIL", from the military specifications, and "E" of the AWS-ASTM specifications, designate covered electrodes for shielded-metal-arc welding. The term "N" (or "Ni") is the identifying letter for nickel-base alloys.

c. The letter "N" is always preceded by the digit "3", "4", or "8". The "3N" series electrodes are used for joining nickel-base alloys to themselves. The "4N" series electrodes are used for welding nickel-base alloys where the welds will be diluted with iron, such as in joining a nickel-base alloy to steel or in welding the clad side of nickel-base alloy clad steels. The "8N" series electrodes are used for welding nickel-base alloys where unusually high quality welds are required.

d. Table XI shows the coding system for the digit following the "N", which identifies the welding process for which the filler metal is intended. In general, the four types of filler metals should not be used interchangeably.

e. The last term of the classification designation is always used to identify the alloy type of composition. The coding is shown in Table XII. Nominal chemical-composition electrodes are shown in Table XIII.

TABLE X. TYPICAL MECHANICAL PROPERTIES OF CHROMIUM AND CHROMIUM-NICKEL WELD METAL

(All-weld-metal specimens)

	Yield Strength, psi	Ultimate Strength, psi	Elongation in 2 In., %	Reduction in Area, %	Brinell Hardness
E308	58,000	88,000	40	50	150
E308ELC	55,000	82,000	40	45	150
E309	58,000	88,000	40	50	150
E309Cb	58,000	88,000	35	40	150
E309Mo	58,000	88,000	40	50	150
E310	55,000	85,000	40	45	150
E310Cb	58,000	88,000	35	40	150
E310Mo	55,000	85,000	40	45	150
E312	70,000	100,000	24	30	180
E316	55,000	82,000	40	45	150
E316ELC	53,000	80,000	35	45	150
E317	60,000	90,000	30	40	160
E318	63,000	85,000	30	40	150
E330	52,000	85,000	35	45	150
E347	60,000	90,000	35	45	160
E410	45,000	80,000	32	65	160
E430	53,000	80,000	27	65	165
E502	34,000	72,000	35	65	130

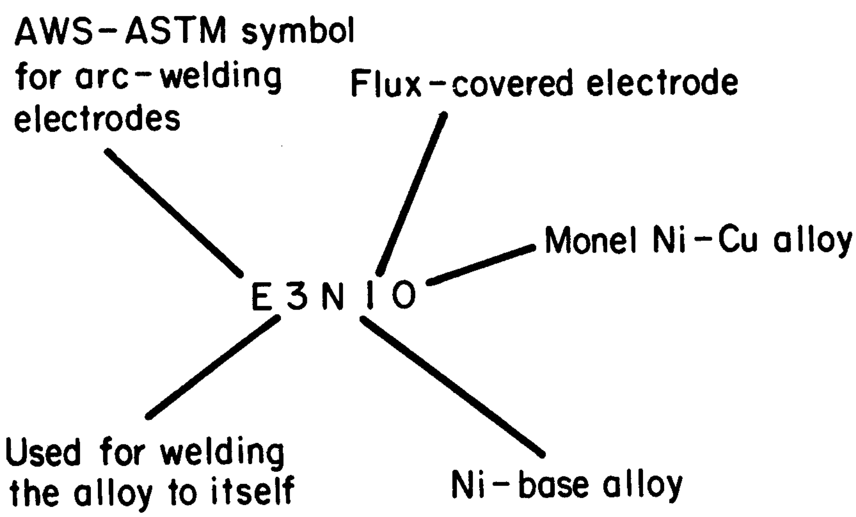


FIGURE 18. MECHANICS OF CLASSIFICATION SYSTEM USED TO IDENTIFY NICKEL ELECTRODES

TABLE XI. WELDING PROCESS IDENTIFYING DIGITS EMPLOYED IN AWS-ASTM AND MILITARY SPECIFICATIONS

Identifying Digit	Welding Process
1	Shielded metal-arc welding
4	Oxyacetylene welding
6	Gas shielded-arc or atomic hydrogen welding
7	Gas shielded-arc, atomic hydrogen or submerged-arc welding

TABLE XII. NICKEL-ALLOY FILLER METAL IDENTIFYING DIGITS

Composition Identifying Terminal Digit or Letter	Alloy Type and Composition
0	Ni-Cu (Monel) alloy
1	Nickel
2	Ni-Cr-Fe (Inconel) alloy
3	Special Ni-Cu-Si (Monel) alloy
4	Age-hardenable ("K" Monel) alloy
5	Ni-Cr-Fe-Cu-Mo (Ni-O-Nel) alloy
9	Age-hardenable Ni-Cr-Fe-Ti-Al-Cb (Inconel "X") alloy
A	Alloy especially alloyed for dissimilar metals welding (Inconel-type)
B	Ni-Mo (Hastelloy B) alloy
C	Ni-Mo-Cr (Hastelloy C) alloy
L	L 605 alloy
M	Ni-Cr-Fe (Nichrome) alloy
N	Ni-Cr-Ti (Nimonic) alloy
W	Ni-Mo-Cr (Hastelloy W) alloy for dissimilar metals welding

TABLE XIII. NOMINAL CHEMICAL COMPOSITION OF DEPOSITED WELD METAL

Nickel and High-Nickel-Alloy Filler Metals.

Designation	Nominal Composition, percent								
	Ni[a]	C	Mn	Fe	Cu	Cr	Al	Ti	Others
Nickel Welding Electrode 131	94.0	0.25	0.25	0.40	--	--	0.50	3.0	--
Nickel Welding Electrode 141	96.0	0.05	0.25	0.30	--	--	0.25	2.2	--
MONEL Welding Electrode 130	68.0	0.15	2.50	0.50	27.00	--	1.00	0.3	--
MONEL Welding Electrode 134	66.0	0.25	2.50	1.00	27.00	--	2.00	0.3	--
MONEL Welding Electrode 140	68.0	0.05	1.20	1.50	26.00	--	0.30	0.7	Cb(+Ta) 1.5
MONEL Welding Electrode 180	63.0	0.03	5.0	0.25	28.00	--	0.30	0.7	Cb(+Ta) 1.5
INCONEL Welding Electrode 132	74.0[b]	0.05	0.75	8.50	--	14.0	--	--	Cb(+Ta) 2.0 Co 0.10
INCONEL Welding Electrode 139	71.0	0.12	0.60	9.00	--	19.0	--	--	Cb(+Ta) 3.0
INCONEL Welding Electrode 142	74.0[b]	0.10	0.40	3.00	--	19.0	--	--	Cb(+Ta) 3.0 Co 0.10
INCONEL Welding Electrode 182	68.0[b]	0.05	7.50	7.50	--	14.0	--	--	Cb(+Ta) 2.0 Co 0.10
NI-O-NEL Welding Electrode 135	38.0	0.05	0.50	31.0	1.8	19.0	--	--	Mo 5.5 Cb (+Ta) 1.0
INCO-WELD A Electrode	73.0[b]	0.05	1.50	8.50	--	14.0	--	--	Cb (+Ta) 2.0 Co 0.10 Mo 0.70
70/30 Copper-Nickel Welding Electrode 187	30.0	0.01	2.00	0.50	67.00	--	--	0.3	--
NI-ROD Welding Electrode	95.0	1.00	0.20	3.00	--	--	--	--	--
NI-ROD 55 Welding Electrode	53.0	1.50	0.30	45.00	--	--	--	--	--

(a) Includes a small amount of cobalt unless marked (b).

Section IV. PROCESS CONTROL

76. PROCESS CONTROL

a. Shielded-metal-arc is a manual welding process. Process control, therefore, lies mainly with the operator. The primary problem in the application of metal-arc welding is the control of three variables -- speed of travel, arc voltage, and amperage. In manual welding, the operator controls the first two of these.

b. The operator's control comes through maintaining the arc and properly positioning the electrode. The arc in metal-arc welding is a gaseous conductor of electricity. It is primarily self-starting, and if extinguished it must be reestablished. The two factors essential for its continuity are proper ionization and a method of feeding the electrode constantly in order to maintain the proper electrode-to-work spacing or arc length. When covered electrodes are used, the arc voltage is dependent on the type of coating and the length of the arc. The arc is maintained by a uniform movement of the electrode toward the work to compensate progressively for that portion which has been melted and deposited in the weld. At the same time the electrode is also advanced progressively in the direction of welding.

c. Current is normally set at the power supply. However, it is possible to have a remote control adjustment at the welder's station. The chemical, metallurgical, mechanical, and electrical variables in the process are to some degree taken into account in the design and manufacture of the equipment and materials used.

Section V. QUALITY ASSURANCE

77. GENERAL

This section deals with quality assurance as it relates to the shielded-metal-arc (SMA) process. Since SMA is a manual process, the quality of welds is largely dependent on the individual welder. Some of the areas of technique that require special attention are discussed below.

a. Angle of Electrode. The quality of a weld is greatly affected by the angle of the electrode in relation to the work. Factors dependent on this position include the ease with which filler metal is deposited, the freedom from undercutting and slag inclusions, and the uniformity of fusion

and weld contour. Recommendations of manufacturers should be followed in all cases.

b. Arc Length. The use of a relatively short arc will keep oxidation and porosity at a minimum. A long arc increases spatter loss and is erratic and inefficient. Constant arc voltage is more easily attained by the use of the drag-type technique.

c. Breaking the Arc

(1) Various procedures are commonly employed to break the arc. One procedure requires that the arc be shortened and the electrode moved quickly sideways out of the crater. This method is used in manual welding when electrodes are changed and the weld is to be continued from the crater. In another procedure, the electrode is held stationary long enough to fill the crater and is then gradually withdrawn. This method is used in manual, semiautomatic welding when either full or partial crater elimination is desired.

(2) When the arc is re-established in a crater (first procedure), it should be struck at the forward or cold end of the crater, moved backward over the crater and then forward again to continue the weld. The crater is filled when this procedure is used and porosity and trapping of slag are avoided. This factor is particularly important with low-hydrogen electrodes.

d. Low-Hydrogen Electrodes. Porosity and slag inclusion may be a problem when low-hydrogen electrodes are used unless special techniques are employed. Generally, the currents used with these electrodes are higher than those used with conventional electrodes of the same diameter. The arc should be struck ahead as described above. The arc should be as short as possible. A long arc and "whipping" will result in porosity and entrapped slag.

e. Electrode Care and Selection. Electrodes should always be properly handled and stored to prevent damage to the coatings. Particular care should be taken with low-hydrogen electrodes which may absorb moisture during storage or with prolonged exposure to high humidity on the job. If it becomes necessary to lower the moisture content, the classification and moisture content desired determine the temperature and length of time for baking. Required baking conditions may be as long as 3 hours at 700 F. The proper electrode for the particular job should

always be used. Care should be taken not to mix electrodes in storage, to prevent using the wrong type unintentionally.

f. Equipment. It is essential to good quality to use the proper equipment for a particular welding application. This would include electrode holders, cables, connections, and clamps. The condition of the equipment is equally important. Proper equipment is necessary not only for quality, but for operator safety.

Section VI. WELDING SAFETY

78. GENERAL

Welding safety as it pertains to welding power supplies was discussed in Chapter 3. The discussion presented here is general in nature and applicable to all welding processes.

79. OPERATION AND MAINTENANCE

a. When electric generators powered with internal-combustion engines are used inside buildings or confined areas, extreme care must be exercised to conduct the engine exhaust to the outside atmosphere. The engine exhaust gives off carbon monoxide, which can prove fatal in poorly ventilated spaces.

b. Do not allow power-supply cable used for portable welding machines to become entangled with the welding cables, or to be near enough to the welding operation to sustain possible damage to the insulation from sparks or hot metal. Where practical, sufficient permanent outlets should be installed so that it will not be necessary to have extensive cables strewn about.

c. Welding leads and primary power-supply cables should be kept clear of ladders, passageways, and doors. Cables used for power service to portable machines and welding leads should be kept out of places where there is possibility of machines or trucks running over them. Repair or replace defective cable immediately. Use insulated cable connectors of the the locking-joint type, having a capacity no less than the capacity of the cable. Disconnect power before splicing any cable. Welding cables should be kept dry and free from grease and oil. They should be arranged in such a manner that they do not lie in water or oil, in ditches, or on bottoms of tanks.

d. Do not weld without all electrical connections, power supply, welding leads, holder, and ground clamp being secure and the welding machine frame well grounded. The work clamp must be securely attached to the work before any welding is carried on.

e. Open the disconnect switch on the power-supply line whenever arc-welding machines are left unattended.

f. Power-cable receptacles for portable welding machines should be so arranged that it is impossible to remove the plug without opening the power-supply switch, or use plugs and receptacles which have been approved to break full-load circuits of the welding machine.

80. ELECTRIC SHOCK

a. The open-circuit voltages, either a-c or d-c, required for satisfactory welding are usually low by comparison with voltage used on lighting circuits or other portable industrial tools. The fact that they are low may, and does, lead to carelessness; consequently, welding operators should be carefully instructed on how to avoid shock. The danger is particularly present in hot weather, when the welder is sweaty, or when it is wet. He should develop the habit of always keeping his body insulated from both the work and the metal electrode and the holder. He should avoid standing on wet floors or coming into contact with a grounded surface. Particularly, he should never permit the bare-metal electrode holder to touch either his bare skin or any wet covering on his body. Consistent use of well-insulated electrode holders and cables, dry protective coverings on the hands and body, and insulation from ground will be helpful in avoiding contact.

b. Partially used electrodes should be removed from holders when not in use. The welder should have a place to lay down his holder or hang it up when it is not in use in a manner that will avoid contact with persons or conducting objects. However, do not discard partially used electrodes or other stub ends where they may constitute a hazard to workmen in the vicinity.

81. VENTILATION

a. The respiratory health hazards associated with welding operations evolve largely from the inhalation of the gases, dusts and metal fumes produced. Whether or not respiratory damage occurs during welding will depend on the use of whatever precautionary measures have been indicated

by an evaluation of the hazards involved. With only a few, relatively simple precautions, the chance of respiratory damage can be eliminated.

b. The presence of toxic materials to which the welder may be exposed will depend upon the type of welding, the filler and base metals, the presence of contamination on the base metal or of volatile solvent present in the air. The degree of toxicity of these materials can differ greatly. This is possibly best illustrated by Table XIV, which lists several of the more common materials which may be encountered in welding with their 1962 Threshold Limit values. (Threshold Limit is that atmospheric concentration, in milligrams per cubic meter of air, which is felt safe for the normal individual to breathe for 8 hours a day, 5 days a week.) It should be emphasized that this represents only degree of toxicity. Actual hazard, or body damage, cannot occur unless an individual inhales these materials in substantially greater amount for long periods of time.

82. EYE AND SKIN PROTECTION

a. It is very important that the eyes of the welder be protected from the heat and glare of the arc and from the particles of hot metal that may fly up from the work. Colored lenses of various shades are available which filter out the glare of the arc but which permit adequate vision during welding. The lenses are graded by numbers with the higher numbered shades being darker. The shades generally used for arc welding range from numbers 10 to 14. Table XV is a guide for the selection of the proper shade numbers. These recommendations may be varied to suit the individual needs of the welder. However, the deepest shade of filter that permits adequate visibility of the arc should be used.

b. Radiant energy, particularly in the ultraviolet range, presents a far greater intensity in gas-shielded arc welding than during shielded metal-arc welding (with covered electrodes). This hazard is of significance to the bare skin and to the unprotected eyes. The greater intensity of the ultraviolet radiation also causes rapid disintegration of cotton clothing. In gas metal-arc welding, the radiation intensity 2 feet from the arc will produce reddening of the skin in a few seconds and a severe skin burn in a few minutes. A large portion of this radiation may also be reflected from bright or light colored surfaces.

c. The welder should wear clothing to cover all exposed skin areas. Shirts should be dark in color to reduce reflections, thereby preventing ultraviolet burns to the face and neck underneath the helmet. Exposed cotton clothing should not be worn when gas-shielded arc welding.

TABLE XIV. THRESHOLD LIMIT VALUES FOR MATERIALS WHICH ARE COMMONLY ENCOUNTERED IN WELDING

Common Materials Which May Be Encountered in Welding	Threshold Limit Values, Milligrams Per Cubic Meter Of Air
Antimony	0.5
Arsenic	0.5
Beryllium	0.002
Carbon dioxide	9,000.
Carbon monoxide	110.
Cadmium oxide fumes	0.1
Chromates (as CrO_3)	0.1
Fluoride	2.5
Hydrogen fluoride	2.0
Iron oxide fumes	15.
Lead	0.2
Magnesium oxide fumes	15.
Manganese	5.
Mercury	0.1
Molybdenum	5.
Nitrogen dioxide	9.
Nickel carbonyl	0.007
Ozone	0.2
Phosgene	4.
Selenium	0.1
Tellurium	0.1
Titanium dioxide	15.
Uranium	0.05
Vanadium	0.1
Zinc oxide fumes	15.
Zirconium	5.

TABLE XV. RECOMMENDED SHADE NUMBERS FOR EYE PROTECTION DURING ARC WELDING

Welding Operation	Shade No.
Shielded Metal-Arc Welding	
1/16" - 5/32" electrodes	10
3/16" - 1/4" electrodes	12
5/16" - 3/8" electrodes	14
Gas Metal-Arc Welding	
Nonferrous materials	11
Ferrous materials	12
Gas Tungsten-Arc Welding	
Nonferrous materials	11
Ferrous materials	12
Plasma-Arc Welding	11-12

d. It is necessary for welders to be equipped with shields or helmets that will protect not only the eyes but also the skin because of the intensity of the ultraviolet and infrared rays. The arc should not be struck without having such a helmet or shield over the face. Welders should wear suitable goggles to protect the eyes when removing slag from welds and when grinding or chipping welds.

e. Personnel other than the welder who are in the area where the welding is being done must also be protected from the harmful rays given off during arc welding. Where the work permits, the welder should be enclosed in an individual booth painted with a nonreflecting paint or enclosed with noncombustible screens. Where arc welding is regularly carried on in a building, the walls of the welding bay should be painted a nonreflecting color to prevent flickering reflections.

CHAPTER 5

INERT GAS SHIELDED-NONCONSUMABLE ELECTRODE PROCESSES

Section I. INSERT GAS SHIELDED TUNGSTEN-ARC (GTA) WELDING

83. DEFINITION

The inert gas shielded tungsten-arc process uses a nonmelting tungsten electrode. The welding arc is struck between the tungsten electrode and the work and produces the heat necessary for melting the edges or surfaces of the parts to be joined. A blanket of inert gas shields the end of the electrode, the arc, and the molten metal from the atmosphere. Where required, filler metal may be added by feeding it into the arc. The process is illustrated in Figure 19. This process is commonly known as tungsten inert gas (TIG) welding.

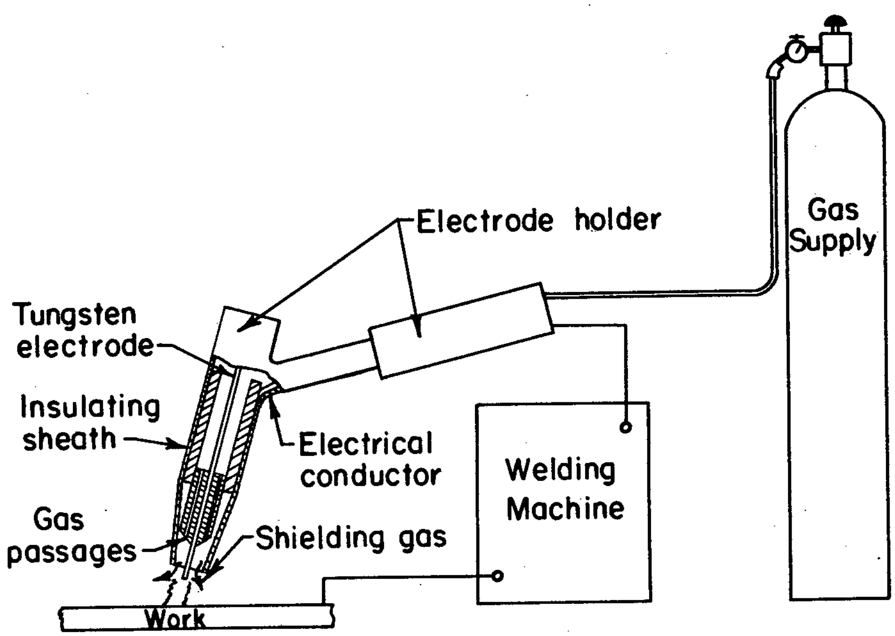


FIGURE 19. SCHEMATIC DIAGRAM OF THE GAS TUNGSTEN-ARC WELDING PROCESS

84. IMPORTANCE AND USES

a. Gas tungsten arc is a very versatile welding method and can be used on most metals presently used in industry. These include aluminum alloys, stainless steel, magnesium alloys, nickel and nickel-base alloys, copper, silicon-copper, copper-nickel, brasses, silver, phosphor bronze, plain carbon and low-alloy steels, titanium, zirconium, gold, and silver. The process is versatile not only in regard to materials but in regard to products and design applications as well. It has a wide variety of uses in both manual and automatic applications. It has also been used for welding various combinations of dissimilar materials, for hard surfacing of steels, and for local melting of metals.

b. A particular application of the process is the welding of very light-gage materials. Because it offers precise heat control and the ability to weld with or without filler metal, it is one of the few processes that can be used on such materials, especially where quality and finish are of great importance. Products in this line include transistor cases, instrument diaphragms, and delicate expansion bellows. The gas-tungsten-arc (GTA) process is not competetive for heavier gages of material where its speed is reduced by the need for filler metal.

c. Good GTA welds are free of porosity, slag inclusions, and contamination from oxygen and nitrogen in the air. They are generally stronger, more ductile, and have better corrosion resistance than other types of arc welds. With GTA welding, the welding heat, amount of penetration, and bead shape can be very accurately controlled. Interpass or elaborate postweld cleaning operations are not needed, as there is no spatter or slag crust with GTA welds and the bead surface is smooth and uniform. Where good as-welded appearance is required, GTA welds can be made without adding filler wire so that the bead buildup is minimized.

85. THEORY

a. The electrode used in GTA welding is generally tungsten or a tungsten alloy, but it may be graphite. An inert gas, fed through the torch, shields the weld zone, the molten metal, and the electrode from the atmosphere. The heat from the arc between the electrode and the workpieces melts the abutting edges of the workpieces. They are joined as the weld metal solidifies.

b. In this process, the inert-gas atoms are ionized and the arc is produced by the passage of current through this ionized gas. The ionized atoms lose electrons, leaving them with a positive charge. The positive ions then flow from the positive to the negative pole of the arc and the electrons from the negative to the positive pole.

86. WELDING CURRENT

a. General. GTA welding may be used with either an a-c or d-c power supply. The two produce different weld characteristics, so one may be better suited than the other for a specific application.

b. Direct Current. Direct-current welding may use either a straight or reverse polarity hook-up. In the former the electrode is negative and the work positive. Reverse polarity is the opposite of this. These connections are shown in Figures 20 and 21.

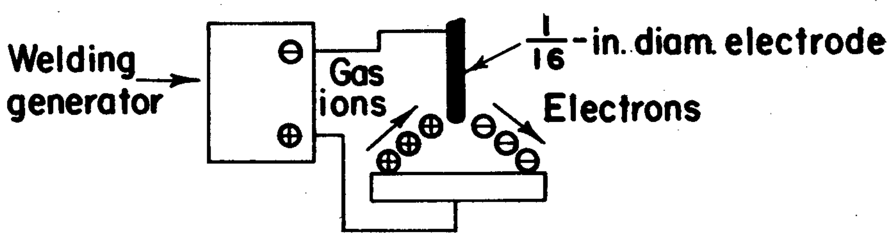


FIGURE 20. DIRECT-CURRENT STRAIGHT-POLARITY CONNECTION FOR GAS TUNGSTEN-ARC WELDING

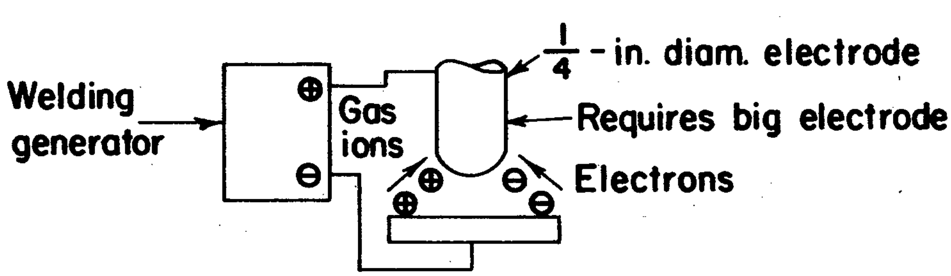


FIGURE 21. DIRECT-CURRENT REVERSE-POLARITY CONNECTION FOR GAS TUNGSTEN-ARC WELDING

(1) Straight polarity is much more widely used for GTA welding because of several distinct advantages. Essentially, the difference between the two, so far as their effect is concerned, is that in straight polarity the workpiece receives extra heat due to the electron flow; in reverse polarity, the electrode is exposed to the extra heat. Because of this, straight polarity produces a deeper, narrower weld puddle (Figure 22). This results in less severe contraction stresses and less trouble with hot cracking. The greater heat input in straight polarity allows faster welding speeds and less distortion of the base metal. Finally, because the electrode is not heated as much as in reverse polarity, smaller electrodes can be used with straight polarity.

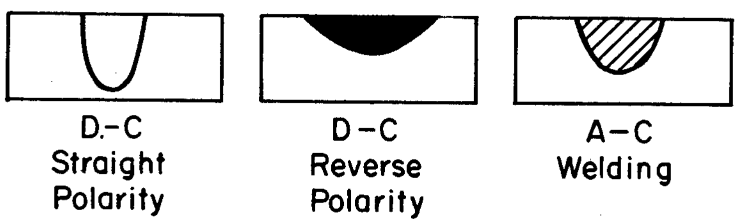


FIGURE 22. GAS TUNGSTEN-ARC WELD CONTOURS FOR D-C STRAIGHT-POLARITY, D-C REVERSE-POLARITY, AND A-C OPERATIONS

(2) The one advantage of reverse polarity is that it exerts a cleaning action on the weld metal. The exact reason for this is not known, but it appears that either the electrons leaving the plate, or the ions striking it, tend to break up surface oxides and dirt. This cleaning action is quite important in the welding of aluminum and magnesium, but seems to be of little importance with other metals.

c. Alternating Current. When alternating current is used for welding, it is generally necessary to introduce an additional high-voltage, high-frequency current. In theory, a-c welding is a combination of direct-current straight polarity and direct-current reverse polarity. In practice, however, the flow of current in the reverse polarity direction is prevented to some degree by moisture and oxides on the plate. This is called

rectification. An additional high-frequency current will form a path for the welding current by jumping the gap between the electrode and workpiece and piercing the oxide film. This offers several advantages:

(1) The arc may be started without touching the electrode to the workpiece

(2) Better arc stability is obtained

(3) A longer arc is possible

(4) Welding electrodes have longer life

(5) The use of wider current ranges for a specific diameter electrode is possible.

Figure 22 shows a typical a-c weld compared to the two d-c welds. Table XVI indicates the applicability of the three current types for various materials.

87. CLEANING

If acceptable welds are to be obtained with GTA welding, proper cleaning of the workpieces is essential. Cleaning is generally more critical than for shielded metal-arc welding. All oxide, scale, oil, grease, dirt, and rust must be removed from the work surface. The type of metal will determine to some extent what cleaning method should be used. However, for smaller assemblies, manual cleaning is usually sufficient. This may be with a wire brush, steel wool, or solvent. Vapor degreasing or tank cleaning will probably be both better and more economical for larger assemblies or on a production basis.

88. WELD BACKUP

a. For several reasons it is often necessary to back up a weld when using the GTA process. The backup may physically support the weld puddle, or it may draw off some of the arc heat from the workpiece and thus prevent the weld puddle from dropping through. With light-gage materials, a backup protects the underside of the weld from atmospheric contamination which could result in porosity or poor surface appearance.

b. A weld can be backed up by (1) metal backup bars, (2) an inert-gas atmosphere on the weld underside, (3) a combination of these two, or (4) a

TABLE XVI. CURRENT SELECTION FOR GAS TUNGSTEN-ARC WELDING

Material	Alternating Current[a]			Direct Current					
	Stabilized			Straight Polarity			Reverse Polarity		
	Excellent	Good	Not Recommended	Excellent	Good	Not Recommended	Excellent	Good	Not Recommended
Magnesium up to 1/8 in. thick	X					X		X	
Magnesium above 3/16 in. thick	X					X			X
Magnesium castings	X					X		X	
Aluminum up to 3/32 in. thick	X					X		X	
Aluminum over 3/32 in. thick	X					X			X
Aluminum castings	X				X				X
Stainless Steel		X		X					X
Brass alloys		X		X					X
Silicon copper			X						X
Silver		X		X					X
High-chromium, nickel-base, high-temperature alloys		X		X					X
Silver cladding	X					X			X
Hard facing	X			X					X
Cast iron		X		X					X
Low-carbon steel, 0.015 to 0.030 in.[b]		X		X					X
Low-carbon steel, 0.030 to 0.125 in.			X	X					X
High-carbon steel, 0.015 to 0.030 in.		X		X					X
High-carbon steel, 0.030 in. and up		X		X					X
Deoxidized copper[c]			X	X					X

(a) Where alternating current is recommended as a second choice, use about 25% higher current than that recommended for DCSP.

(b) Do not use alternating current on tightly jigged parts.

(c) Use brazing flux or silicon-bronze flux for 1/4 in. and thicker.

flux backing, painted or taped on the weld underside. A commonly used type of backup bar is shown in Figure 23. Where weld composition is very critical and all atmospheric oxygen must be excluded from the underside, an atmosphere of gas can be introduced into the relief groove.

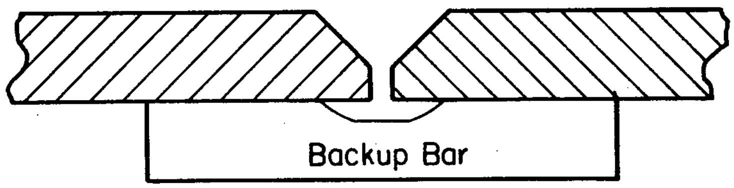


FIGURE 23. GROOVED BACKUP AS TYPICALLY USED IN GAS TUNGSTEN-ARC WELDING

89. EQUIPMENT AND CONTROLS

a. General. The following equipment is needed for GTA welding: an electrode holder (torch) equipped with gas passages and nozzle for directing the shielding gas around the arc; nonconsumable electrodes; a supply of shielding gas; a pressure-reducing regulator and flowmeter; and a power unit. If the electrode is water cooled a supply of cooling water will be needed. Also needed will be a gas flow control valve and a convenient means of switching power on and off at the start and finish of welds. The nature of the individual components will vary considerably with design, type of work, and power requirements.

b. Torches. Torches are made so that electrodes and gas nozzles can be readily changed, either for different sizes or for replacement. The torches may be either water or air cooled. Each torch is designed for particular applications and current requirements.

c. Power Supplies. There are a-c and d-c power units designed specifically for use in GTA welding. These are equipped with automatic means for controlling gas and water flow at the start and stop of welding. However, standard d-c power supplies normally used for welding with covered electrodes may also be used.

d. Gas Regulators. Regulators are similar to those used for control of oxygen in gas cutting. The equipment usually consists of a single or dual stage pressure-reducing regulator and a gas-measuring flowmeter. These may be incorporated into the same unit.

e. Mechanized Equipment. Automatic welding equipment is more complex than manual welding equipment. Various devices and controls may be added to the automatic welding equipment, depending on the application. These may include electronic voltage controls which maintain a uniform arc length and voltage; various work-handling and clamping equipment, torch positioning and moving devices; and filler-wire feed mechanisms. Such equipment usually includes a means of initiating the arc and of controlling the flow of shielding gas and cooling water to the torch.

90. ELECTRODES

a. As noted before, tungsten, tungsten-alloy, or graphite electrodes may be used for GTA welding. The tungsten-alloy electrodes are probably most commonly used. These are alloyed with 1 to 2 percent of thorium or zirconium. When using a-c, high-frequency current, these alloy electrodes have a greater current-carrying capacity for a given electrode size. They also provide a more stable arc at low current values and offer longer life because of less deposit of tungsten in the welds.

b. Although the electrodes are considered nonconsumable, they do break on occasion and are subject to slow erosion, so they must be replaced from time to time. Electrode diameters vary from 0.020 to 0.25 inch, and they are usually 7 inches long. The current-carrying capacity of an electrode will increase directly with its diameter. Current density in larger electrodes can be increased by tapering the arc end. This also serves to improve arc stability. The electrode diameter should be selected to correspond with the welding current.

91. SHIELDING GASES

a. General. Argon is the shielding gas most commonly used for GTA welding. Helium and a mixture of argon and helium are also used. Many other gases have been tried and found to be less reliable, although some have been found useful for specific purposes. For example, nitrogen can be used in welding copper. There are several factors that explain the preference for argon and helium:

(1) They are completely inert and will not combine with other elements

(2) They are relatively insoluble in molten metals

(3) They favorably influence arcing characteristics

(4) They are readily available at a reasonable cost.

There are other inert gases such as neon, xenon, and krypton, but they are too rare and costly. Other gases lack the necessary inertness and insolubility.

b. Argon. Argon has several advantages to explain its more widespread use:

(1) Smoother, quieter arc action

(2) Lower arc voltage at a given current value and arc length

(3) Greater cleaning action when using a-c to weld such metals as aluminum and magnesium

(4) More readily available and cheaper

(5) Lower flow rates for good shielding

(6) Better cross-draft resistance

(7) Easier arc starting.

Argon's lower arc-voltage characteristic is especially useful in certain applications. When welding thin material, it lessens the possibility of burn-through. In overhead welding it decreases the tendency for the metal to sag or run. Figure 24 shows arc voltage characteristics for argon and helium, and Figure 25 shows the same for mixtures of the two.

c. Helium. The higher arc voltage of helium is desirable when welding thick material and metals with high heat conductivity. Thus, helium is used more often with heavy materials than with light stock. The higher arc voltage is also an advantage in high speed mechanized welding of stainless steel tubing. Where a balance of characteristics is desired, argon-helium mixtures are useful.

d. Hydrogen Additions. The addition of hydrogen to either argon or helium will provide even higher arc voltage and heat than helium alone. This can be seen in Figure 25. However, these mixtures can injure many metals and alloys, including all aluminum, copper, and magnesium-base alloys. Thus, there are only a few metals for which such a mixture is useful. Presently, these include certain stainless steels and nickel alloys.

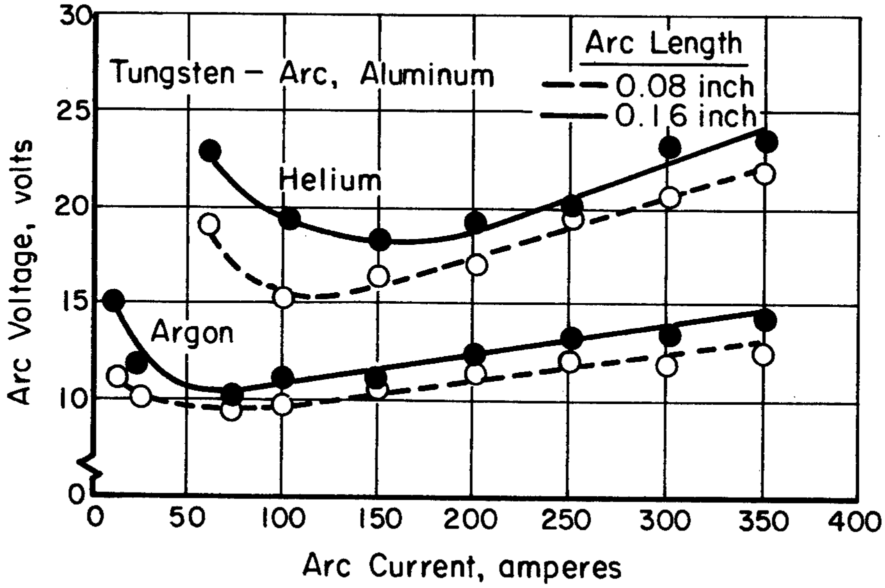


FIGURE 24. ARC-VOLTAGE CHARACTERISTICS OF ARGON AND HELIUM

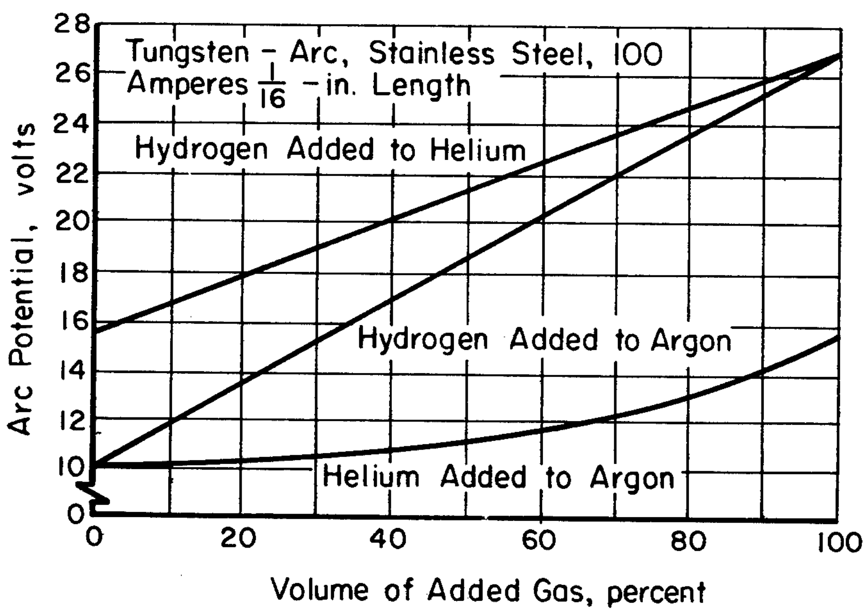


FIGURE 25. ARC-VOLTAGE CHARACTERISTIC OF MIXTURES OF ARGON AND HELIUM WITH HYDROGEN

e. Gas Purity. The purity of the gas used for shielding may have an effect both on weld speed and on weld quality. The extent to which this is true will vary with the particular metal being welded. For example, impurities of only a few hundredths of a percent can cause serious damage to titanium and zirconium. On the other hand, carbon steel and copper are little affected by several times this amount. A small percentage of impurity will not generally affect stainless steel, but most nonferrous metals are best welded with high-purity shielding gas. Commercially available argon and helium now have high purity, averaging over 99.95 percent and sometimes exceeding 99.995. Oxygen and nitrogen are the most common impurities found in shielding gases, although there is some oil and water vapor found. These impurities when found at the welding torch are not necessarily from the original gas supply. There may be leaks in the hose lines leading to the torch, or merely diffusion of water or gases through the lines. For this reason, it is best to use synthetic rubber or plastic tubing for hoses, as these materials are more impervious to gas diffusion than natural rubber.

92. QUALITY ASSURANCE

a. The welding preparation necessary to insure good quality GTA welds has already been discussed to some extent in the section on theory. This involves cleaning of the joint and the use of weld backing. It is also essential that filler wire be clean. Filler wire is properly cleaned before packaging, so a freshly opened package should be acceptably clean. If wire has been previously opened, however, it should be very carefully checked for cleanliness. Wire should not be handled with greasy hands or gloves. Where a mechanical wire feeder is used, it should be kept clean and the drive rolls should be kept free of oil.

b. It is important to use the proper size filler wire. The size will depend on the thickness of material to be welded and the current setting. If the filler wire is too large, too much heat is used to melt the wire and the weld may lack penetration. If the filler wire is too small, the welder may have difficulty feeding it into the weld pool fast enough to build up the weld bead properly.

c. Some of the common GTA-welding problems and their solutions are discussed in the following paragraphs. Most of these problems can be related to either the shielding gas or tungsten electrode.

(1) Arc Wander. Movement of the arc away from the center line and towards one side of the joint is termed arc wander. There are several factors that can cause this. If the arc moves rapidly from one side of the joint to the other, either a contaminated or a blunt electrode is the cause. If the movement is slow, or if the arc stays on one side of the joint, magnetic fields or air drafts are the cause.

(a) Electrode Contamination. The electrode may become contaminated by contact with the weld puddle, the filler wire, or because of use at excessively high welding currents. In any case, a large ball of molten, contaminated tungsten forms on the tip of the electrode and causes the arc to move about. The ball should be removed by regrinding the electrode or by breaking off the end of the electrode and resharpening the point.

(b) Air Drafts. If the arc is forced off center by air drafts, screens should be set up to protect the arc.

(c) Arc Blow. Magnetic fields may cause arc movement to the side of the joint or backward slanting of the arc. This problem usually can be solved, or at least minimized, by changing the position of the ground cable attachment. Sometimes the steel jaws of the jig will become magnetized and disrupt the arc. These magnetic fields will not occur if the clamping jaws are made from copper.

(2) Tungsten Pickup in the Weld Metal. Bits of tungsten can be picked up in the weld metal if (1) the arc is struck on the workpiece or (2) the welding current is too high. The first condition can be prevented by using high-frequency starting or by striking the arc on a copper block. Regarding the second condition, the tungsten ball that forms on the end of the electrode when current is too high has been mentioned above. This ball may become so large that it drops into the molten weld puddle.

(3) Weld Metal Porosity. Porosity normally occurs in the underside of a root pass of a butt joint. If the underside of the joint is not well shielded when the root pass is being welded, the underside will become oxidized. This can be prevented by shielding the underside of the joint with at least a copper backup bar and preferably a gas backup.

(4) Poor Gas Shielding. If the inert-gas shield is not performing properly, air will come in contact with the molten weld metal and hot base plate and cause contamination. When this happens, the weld and adjacent base metal have a black coating. The gas shield can break down for several reasons:

(a) The flow of shielding gas is too low.

(b) The flow of shielding gas is too high. This causes a turbulent flow which may suck air into the gas.

(c) Drafts are blowing the gas shield away.

(d) The gas supply hose, hose fittings, or gas passages in the torch are blocked.

(5) Rough, Dirty Electrode. If the tungsten electrode becomes rough or looks as if it is dirty, air probably is reaching the electrode while it is hot during welding. This air may be occurring because of poor shielding or because of a leak in the gas supply line. If the electrode protrudes too far beyond the end of the gas cup, it may not be shielded properly. Electrode protrusion varies with the torch and cup size. The recommendations of the torch manufacturer should be followed.

(6) Lack of Penetration. Lack of penetration indicates that the weld is not getting enough welding heat. This is usually because current is too low or travel speed too high. With GTA welding it can also mean that the diameter of the filler wire is too large or that the filler wire is being dipped in the weld puddle too frequently. For proper penetration, these factors must be carefully balanced, and this depends in large part on the skill of the operator.

Section II. GAS TUNGSTEN-ARC SPOT WELDING

93. DEFINITION

a. In spot welding, the two pieces of metal to be joined are overlapped and heated in one spot to cause fusion across the faying surface in a local area to produce a weld. Spot welds can be made by resistance-welding and arc-welding techniques.

b. In gas tungsten-arc spot welding, the heat is provided by an arc struck between a nonconsumable tungsten electrode and the work. The electrode, arc, and work, are shielded from the atmosphere by an inert gas.

c. With resistance-spot welding, melting starts at the interface between the two workpieces and proceeds outward. With arc-spot welding, melting starts at the surface of the top sheet where the arc strikes the work and proceeds through the top sheet, and down into the bottom sheet.

94. IMPORTANCE AND USES

a. Gas tungsten-arc spot welding has several advantages over resistance-spot welding.

(1) Arc-spot welding can be used when there is access to only one side of the assembly being welded.

(2) Only enough welding force is required to hold the pieces together; no forging pressure is required as in resistance welding

(3) Arc-spot-welding equipment is highly portable

(4) Large assemblies do not have to be moved for successive welds

(5) Thin sheet can be welded readily to thick parts

(6) Arc-spot-welding equipment costs much less than does a resistance-spot welder.

b. The process is now used in the automotive industry for spot welding bodies, transmissions, and other parts. It is also used for spot welding a great many other sheet-metal parts, including refrigerators and other household appliances, doors, and jacketed kettles.

c. Arc-spot welding is not as fast as resistance-spot welding, so the cost per weld is higher; therefore, if existing resistance-spot-welding equipment can satisfactorily do a given job, it should not be indiscriminately rejected for an arc-spot welder.

95. THEORY

a. GTA spot welding can be done automatically, but is usually applied manually. It is best adapted for welding sheet metal parts of from about 0.025 to 0.090 inch thick. With careful control, it is possible to weld either thicker or thinner sheets.

b. As with other arc-welding processes, the arc in arc-spot welding is established between the end of an electrode and the workpiece. However, the arc is held in one spot instead of being moved along the workpiece. The heat of the arc melts a round spot in the workpiece. This molten spot extends through the top sheet into the bottom sheet of the two being joined. When this molten spot freezes, it forms a round "spot" weld joining the two pieces together.

c. Precise timing of the welding operation is required to control the amount of penetration of the bottom sheet. Timing devices are incorporated into the control systems that are used to regulate the various welding conditions.

d. Two things are very important to the production of satisfactory welds with this process. First, the surfaces of the parts to be joined must be very clean, and secondly, the two parts to be joined must be held together in close contact during the welding operation.

e. Occasionally, filler metal is added to improve surface appearance by filling in depressions on the surface of the weld spot. Filler metal may also be added when the material being welded is crack sensitive.

f. Welding may be done with either alternating or direct current. Direct current with straight polarity is most often used because it produces a deeper and narrower weld puddle, which penetrates more easily through to the bottom sheet and produces less severe contraction stresses as the weld cools.

g. Either argon or helium shielding gases or a mixture of the two may be used. Helium provides greater penetration with a smaller weld-spot diameter than does argon. Argon is generally used when the top sheet is thinner than 1/16 inch and no joint backing is used. When the top sheet is thicker than 1/16 inch, or whenever joint backing is used, helium is used as the shielding gas. Sometimes a mixture of about two parts of helium and one part of argon is used for arc-spot welding stainless steel.

96. EQUIPMENT AND CONTROLS

a. Torches for manual welding are pistol-like and have a vented, water-cooled nozzle. Their operation is controlled by a trigger switch. For automatic operation other types of torches are available. Automatic setups generally include controls for turning on and shutting off the welding power, cooling water, and gas. A trigger switch in the torch handle activates these controls in most cases. A typical manual welding setup is shown in Figure 26.

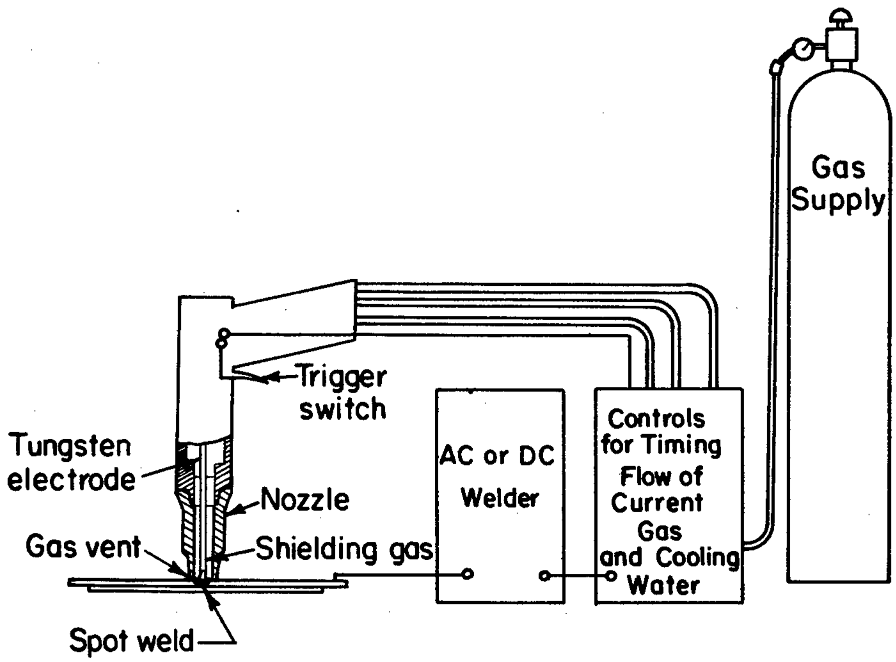


FIGURE 26. SCHEMATIC DIAGRAM OF SETUP FOR MANUAL GAS-TUNGSTEN-ARC SPOT WELDING

b. Equipment is available for both a-c- and d-c-type power. With a-c, the spark is initiated by a high-frequency arc-stabilizing unit. There are three methods of starting when d-c is used: (1) a spark from a high-frequency unit, (2) mechanical retract starting in which the electrode touches the work initially and is retracted when the arc starts, and (3) pilot-arc starting, in which a low-current arc is maintained between the electrode and the torch nozzle to maintain an ionized gaseous environment.

c. Precise timing of the welding operation is required to control the depth of penetration into the bottom sheet. This is accomplished by using an arc timer to extinguish the arc after a predetermined time has elapsed as required to get the desired amount of weld penetration.

97. QUALITY ASSURANCE

a. It is important to have good heat transfer between the pieces to be welded. Penetration of the bottom piece is accomplished by the transfer of heat from the top piece to the bottom piece. If the heat cannot transfer easily across the interface between the two pieces, the heat reaching the bottom sheet may be insufficient to cause melting of the bottom sheet.

(1) Films of dirt, grease, scale, etc., on the surfaces of the pieces will hinder heat transfer. Usually, enough heat will transfer across the dirty surfaces to cause some melting in the bottom sheet. The size of the weld, however, will be smaller and the strength will be lower than if the surfaces were clean.

(2) The pieces being arc-spot welded must be held tightly together during the welding operation. A weld between parts that are in loose contact or that may be separated slightly will be smaller than desired, if, in fact, a weld is actually made. If the surfaces of the parts are clean, the force exerted by the operator in pressing the pieces together with the welding gun usually is sufficient to obtain good contact between the pieces.

b. The important welding conditions that must be preselected are arc length, welding current, and welding time.

(1) An increase in the arc length will increase the surface diameter of the spot weld but decrease its penetration into the bottom sheet. If the arc length is set too short, arc starting may be erratic and the electrode may freeze to the weld. Excessive arc length will result in a weak weld because the penetration into the bottom part will be very shallow.

(2) An increase in the welding current will increase the depth of penetration into the bottom part if the parts are of approximately the same thickness. The diameter of the weld also will be increased slightly. If the bottom part is considerably thicker than the top part, increasing the current will increase the weld diameter with little increase in penetration.

(3) Increasing the weld time will increase the diameter of the weld but will have little effect on the depth of penetration.

Section III. PLASMA-ARC WELDING

98. DEFINITION

a. In plasma-arc welding, fusion is obtained by the heat of a constricted electric arc-gas mixture called a plasma. The constricted arc offers four advantages over open arc processes such as gas-tungsten arc. These are:

(1) Greater energy concentration

(2) Improved arc stability

(3) Higher heat content

(4) High velocity and momentum of the plasma effluent.

b. Plasma for welding is generated by one of two modes: (1) a transferred arc or (2) a nontransferred arc. A transferred arc is established between the workpiece and an electrode within the torch. A nontransferred arc is established between the constricting orifice and the center electrode inside the torch. The two modes are shown in Figure 27. Transferred arcs transfer more energy to the workpiece, but require an electrically conductive workpiece. When the workpiece is nonconductive, or when lower energy concentration is desired, a nontransferred arc is used.

99. PRINCIPLES OF OPERATION

a. Although an inert gas is used, plasma-arc welding differs from gas-tungsten arc in its use of a constricting orifice. The transferred arc mode is most commonly used. Plasma-arc welding offers greatest advantages in material thicknesses greater than 3/32 inch, where a significant difference can be noted in the weld puddle. This is known as the "keyhole" effect, and is shown in Figure 28. At the leading edge of the weld puddle,

the arc passes completely through the workpiece because of the force of the plasma jet. This produces the keyhole. As the arc moves forward, surface tension causes the molten metal to flow around this keyhole to form the weld. Observation of the keyhole during welding is an indication of complete and uniform weld penetration.

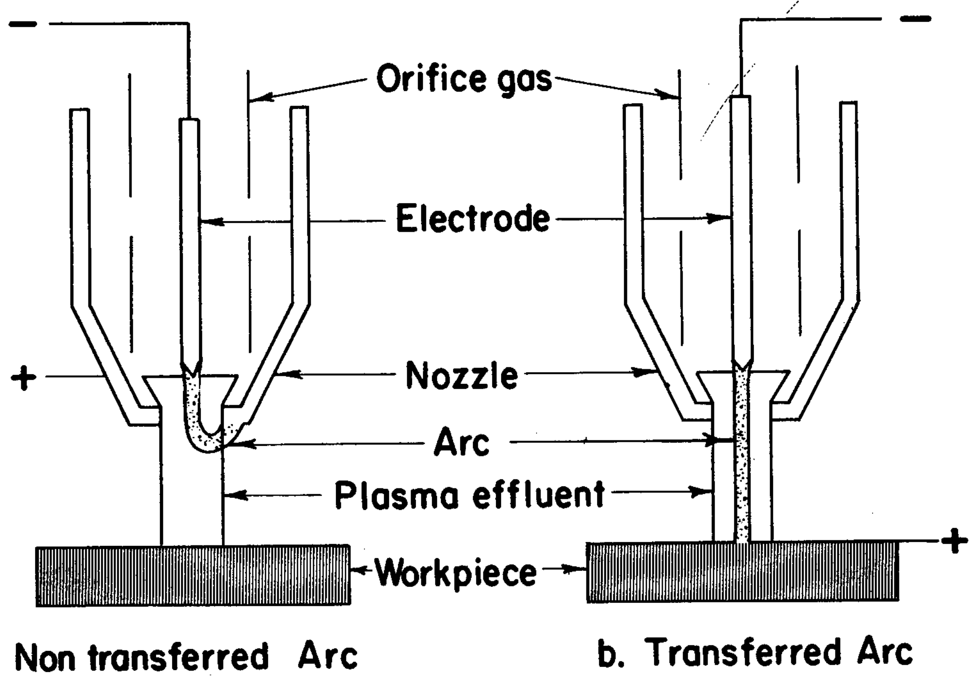


FIGURE 27. MODES OF PLASMA GENERATION FOR WELDING NONTRANSFERRED ARC AND TRANSFERRED ARC

b. Some typical nozzle designs for plasma-arc welding are shown in Figure 29. The process uses both single- and multi-orifice nozzles. Multi-orifice nozzles permit higher welding speeds for many applications by reducing the tendency for weld undercut.

c. Poorer joint alignment and greater variations in arc length can be tolerated with the plasma-arc process than with gas tungsten-arc process. Joint alignment is less critical because the arc has greater stability and the plasma is less likely to be deflected to the high side of a mismatched joint. Arc-length variations have little effect on heat input or welding performance. This is due to the columnar shape of the plasma-arc as opposed to the conical arc of the gas tungsten-arc process in which the area of arc impingement increases significantly with an increase in arc length.

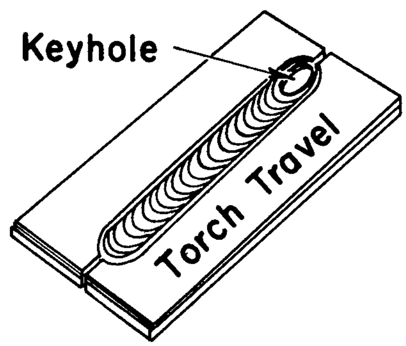


FIGURE 28. KEYHOLE EFFECT IN PLASMA-ARC WELDING

100. IMPORTANCE AND USES

a. Although it is a more complex process, automatic plasma-arc welding offers distinct advantages over either gas tungsten-arc or gas metal-arc welding. It has greater penetration capabilities and can produce extremely narrow (depth-to-width ratio) weld beads at higher welding speeds. Because of this, the degree of distortion is much lower with plasma arc.

b. The full potential of plasma-arc welding is not yet known, but a limited number of applications have been reported. It can be used with many of the common joint types, as discussed in the following paragraphs.

(1) Butt Welds. For a tight butt joint with square edges, plasma-arc welds can often be made in a single pass without the addition of filler metal. If a multiple pass is needed, filler wire must be used. Where material is over 3/32 inch thick, a "keyhole" is formed. This technique has been used with 18Ni maraging steel, 300 and 400 series stainless steel, high-strength steel, and titanium in thicknesses ranging up to 0.250 inch. Aluminum has been butt welded in thicknesses of 0.250 inch.

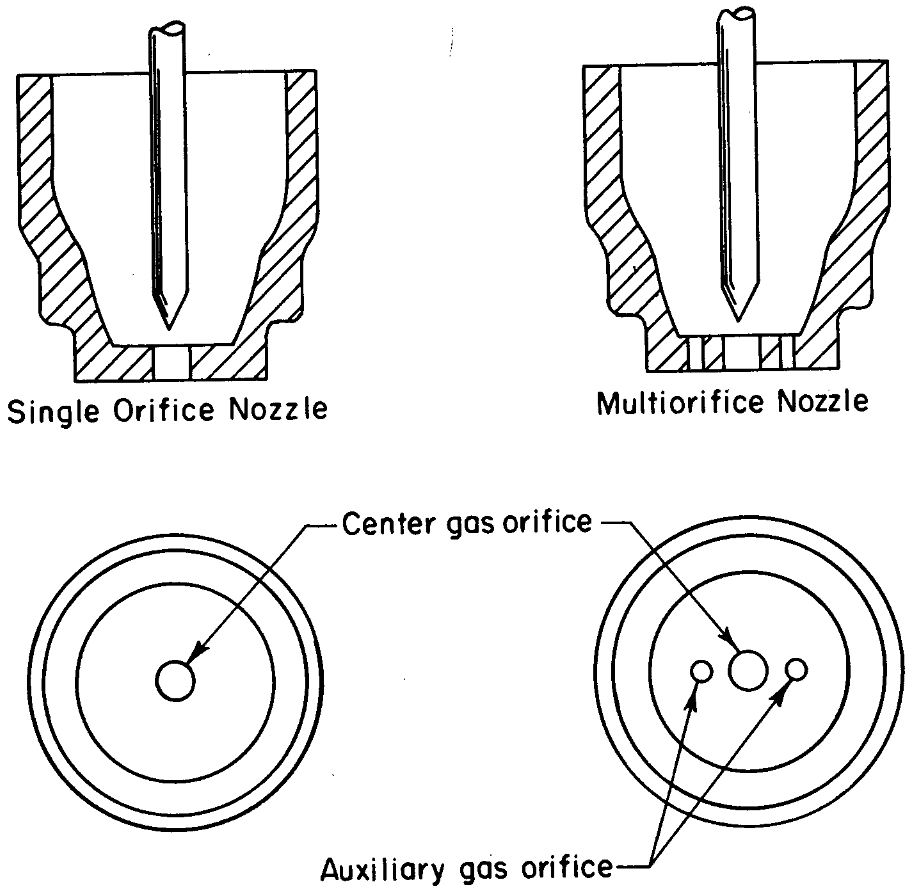


FIGURE 29. TYPICAL SINGLE AND MULTI-ORIFICE PLASMA-ARC WELDING NOZZLES

(2) Thick Materials. Other materials in thicknesses greater than 1/4 inch can be welded using prepared joint designs and multipass welding techniques. Plasma-arc offers greater weld reliability and requires fewer passes than the gas tungsten-arc process when welding thick material. The first pass may or may not use a filler metal, depending on the application. Gas flow must be reduced on subsequent filler passes to prevent excessive agitation of the molten metal in the absence of a keyhole.

c. "T", Slot, or Plug Welds. "T"-shaped structural members have been plasma welded by penetrating through the top plate into the upright member. This provides equally distributed fillets on each side of this member. Plug or slot welds can be made with fixturing that insures adequate interface contact at the weld area and positive hold-down clamping adjacent to the weld.

d. Fillet Welds. Recent changes in the plasma-arc torch to a cone-shaped nozzle have made fillet welding possible. In general, common fillet welding practices apply.

e. Tube Welding. Because it is well suited to continuous welding of uniformly thick material, one of the earliest applications of plasma-arc welding has been in welding longitudinal seams in tubing. It has been successfully used for stainless steel, titanium, and aluminum tubing.

101. EQUIPMENT AND CONTROLS

a. Plasma-arc welding requires a torch, a control unit, a high-frequency generator, a water-pump assembly, and a power supply. For stainless steel and most other metals, d-c straight polarity is used with a tungsten electrode. For aluminum, sponge compacts of zirconium, and other reactive metals, d-c reverse polarity with a water-cooled copper electrode is used.

b. The plasma-arc electrical circuit includes a power supply, a high-frequency generator, and a starting circuit (Figure 32). The power supply, high-frequency generator, and gas and cooling water supplies to the torch are operated and sequenced by a control unit. This control can also be used to operate a wire-feeding device and to initiate torch or work travel mechanisms.

c. Plasma-arc welding uses conventional rectifier-type power supplies or motor generator units. Where hydrogen in the argon-hydrogen gas mixture is less than 7 percent, or argon is used alone, one power supply with an open circuit voltage of 70 v is satisfactory. However, when the hydrogen content exceeds 7 percent, or when helium alone is used, additional open circuit voltage is needed for reliable arc ignition.

102. QUALITY ASSURANCE

a. It has already been stated that plasma arc is a more complex process than gas-tungsten arc. Thus, there are more factors that require control and surveillance from the quality assurance viewpoint. Plasma arc requires slope control of both nozzle gas flow and current to suitably start girth welds and to eliminate the keyhole in the area of weld overlap.

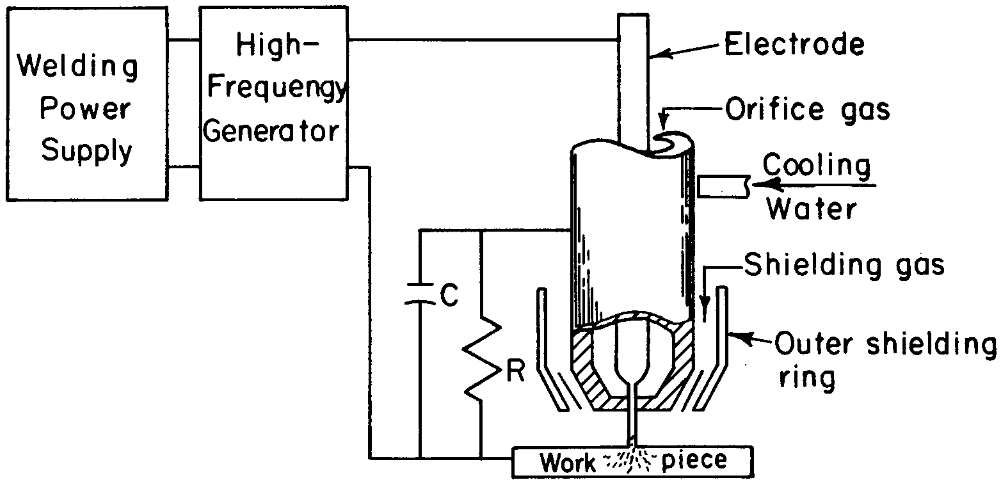


FIGURE 30. ELECTRIC CIRCUIT FOR PLASMA-ARC WELDING

b. Visibility is a limitation of plasma-arc welding. The torch is rather bulky and does not have a protruding electrode to line up with the seam. Auxiliary equipment to insure complete inert-gas shielding of the welding further detracts from visibility. Finally, the addition of filler wire reduces visibility. Because of this, alignment is more difficult, but at the same time more important because of the narrower weld beads and higher welding speeds.

c. Filler wire has the additional effect of increasing the sensitivity to what is known as secondary arcing. This is an arc struck between the torch nozzle and the workpiece. This can be remedied by increasing the torch gas volume, reducing the current value, increasing the orifice diameter, or reducing tungsten setback.

d. Variations in gap width are not as important as in gas tungsten-arc, but do contribute to inconsistent bead contours. When the gap exceeds certain limits, the arc may start to operate as a cutting torch, resulting in holes in the weld bead. The permissable gap is proportional to the thickness of the material, but gap tolerances for different materials have not yet been established.

e. As with gas tungsten-arc, weld speed, current, torch gas flow, orifice diameter, wire speed, electrode set-back, and torch stand-off are interdependent. A change in one often requires a change in one or more of the others.

Section IV. GAS-TUNGSTEN-ARC HOT-WIRE WELDING

103. DEFINITION

Gas-tungsten-arc (GTA) hot wire is a GTA process in which the filler wire is preheated to a temperature close to its melting point before entering the weld puddle. Thus, the tungsten arc does not have to supply the energy required to melt the filler wire.

104. IMPORTANCE AND USES

a. Using the hot-wire process, welds of GTA quality can be made at high speeds. The process is four times faster than welding with the GTA process using a cold filler wire. The only practical limitation on deposition rates is the amount of metal that can be usefully deposited, consistent with good weld bead geometry and mechanical properties. Rates of 16 lb/hr have been achieved in steel. By using torch oscillation, rates up to 20 lb/hr are possible. Figure 31 compares the deposition rates in steel of hot- and cold-wire gas-tungsten arc welding.

b. Hot-wire GTA welding has been used with a variety of steels and nickel alloys. However, it is not recommended for use with aluminum or copper because of the low resistance of filler wires. Other disadvantages include the difficulty of obtaining fracture toughness in some high-strength steel welds equal to that obtained by conventional GTA welding, weld cracking with hot-wire variation on 9 Ni - 4 Co steel, and manual welding is not practical with hot wire variation.

105. THEORY

a. The hot-wire GTA process uses a unique method of filler metal addition in which the wire is melted by passing an a-c current through it. The wire's resistance to the current causes it to heat. The power is so balanced that the wire temperature reaches the melting point at the moment the wire reaches the weld puddle. The "hot-wire" torch follows the regular welding torch and feeds the molten filler wire into the trailing edge of the weld puddle. This allows the operator to see the weld without obstruction.

b. Hot-wire GTA offers the same advantages as conventional GTA welding. It is simple and easy to operate and produces high-quality welds. The weld surface is smooth and post-weld cleaning is not required. In addition, the hot-wire process offers two additional quality benefits: (1) tends to reduce weld porosity by drawing off contaminants on the welding wire before they enter the weld and (2) transfer efficiency approaches 100 percent.

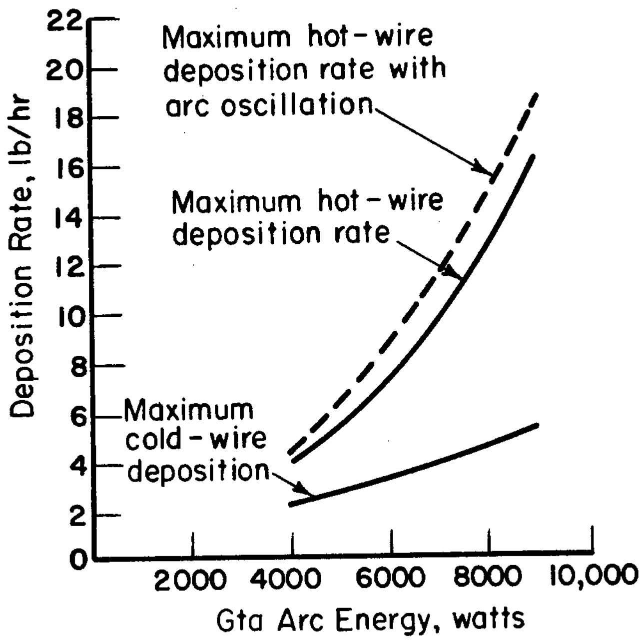


FIGURE 31. COMPARISON OF DEPOSITION RATES IN STEEL WITH THE GTA HOT-WIRE WELDING PROCESS

106. EQUIPMENT AND CONTROLS

a. General. Three additions to regular gas tungsten-arc welding equipment are necessary for hot-wire GTA welding. These are: a hot-wire torch, hot-wire power supply, and wire feeder. A typical installation is shown in Figure 32.

b. Torch. The hot-wire torch transfers the heating current to the wire, guides the wire into the weld puddle, and provides inert-gas shielding as the wire heats. The torch can be used without the gas cup when the wire must be placed very close to the arc for welding thin materials.

c. Power Supply. An a-c, constant potential power source is normally used with hot-wire GTA welding. A rating of 500 amp at 100 percent duty cycle with an open-circuit voltage range of 2 to 40 volts is usual. Units are available with on knob control of wire speed and melting power.

d. Wire Feeder. Wire feeders typically allow speeds ranging from about 50 to 825 in./min.

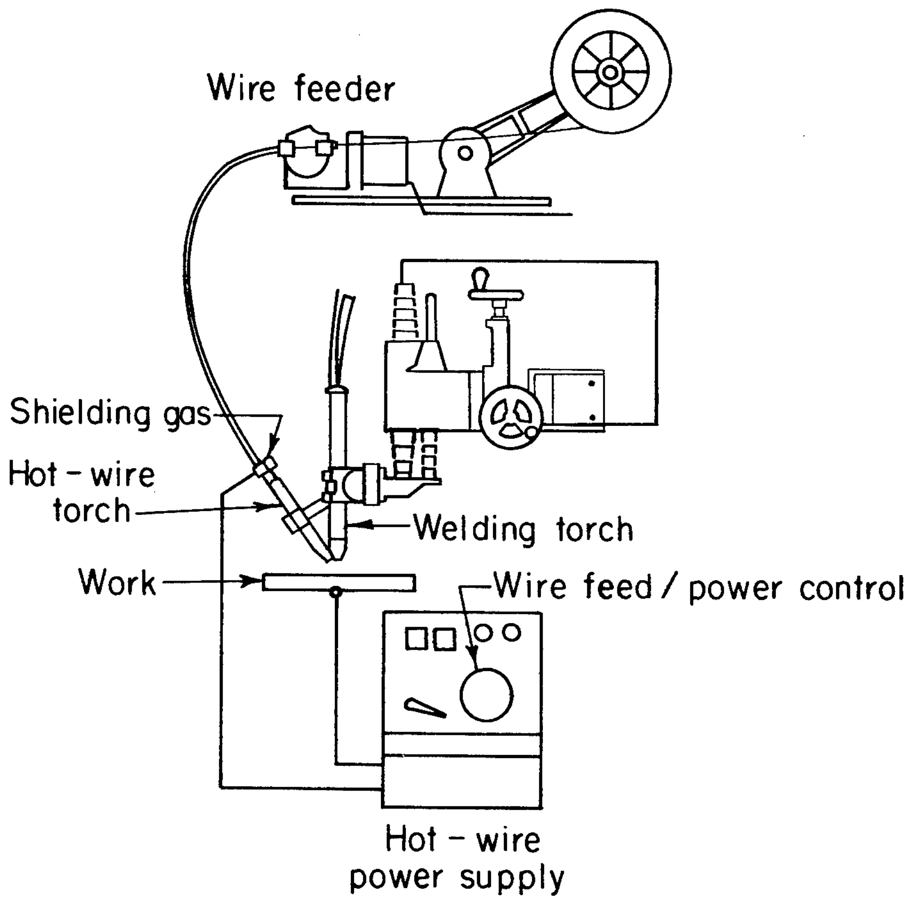


FIGURE 32. TYPICAL GTA HOT-WIRE INSTALLATION

CHAPTER 6

GAS-SHIELDED-CONSUMABLE ELECTRODE PROCESSES

Section I. GAS SHIELDED METAL-ARC

107. DEFINITION

a. Gas shielded metal-arc (GMA) welding is a process that produces fusion by heating with an electric arc between a consumable spooled-wire electrode and the work. The arc and weld puddle are shielded from the atmosphere by a gas or a gas and a flux. The shielding gas protects the molten weld metal from oxidation or contamination by the surrounding atmosphere. The process is also known as metal inert-gas (MIG) welding.

b. There are two basic types of gas metal-arc welding as defined by the type of metal transfer. These are free-flight and short-circuiting transfer. Spray transfer is the principal type of free-flight transfer used. Short-circuiting transfer is sometimes referred to as dip-transfer. These metal-transfer modes were discussed previously in Chapter 2, Paragraph 12c. In free-flight transfer, the metal is transferred across the arc in the form of droplets. In short-circuiting welding, the end of the electrode rapidly and repeatedly touches the weld puddle (short circuits). Each time it touches the puddle, some of the melted electrode wire is transferred to the puddle.

c. The general process of GMA welding will first be discussed in terms of free-flight transfer in this section of Chapter 6. The short-circuiting GMA process and other variations of both the short-circuiting and spray-type-transfer processes will be discussed in later sections of this chapter.

d. The consumable-wire electrode for GMA welding is fed through the torch to the welding arc at the same rate as the heat of the arc melts off the end of the electrode. The shielding gas flows through the torch to the arc area. The melting rate of the filler wire depends on the level of the welding current, but must be the same as the feeding rate to maintain a constant arc length. This means that a constant balance must be maintained between the welding current and wire feeding rate. This can be done in two ways: (1) preset the wire-feed speed and vary the welding current, and (2) preset the current and vary the wire-feed speed.

e. Each of these techniques uses a different type of power source and control circuit. When the wire feed rate is preset, a constant-voltage type of power source must be used. This type of power source is designed to provide a constant arc voltage and length by automatically varying the current. When the current is preset, a constant-current, drooping-voltage type of power source is used. The speed of the wire-feed motors is varied automatically by means of special electrical devices so that a constant arc length is maintained.

108. IMPORTANCE AND USES

a. The gas metal-arc welding process is relatively fast and versatile and can be successfully used with a wide variety of metals and alloys. Aluminum, copper, magnesium, nickel and many of their alloys, as well as iron and most of its alloys, have been successfully welded using the process. Some satisfactory titanium welds have also been made. The process can be operated in several ways, including semi- and fully automatic with conditions set to obtain various types of metal transfer. It can be operated with a pure inert gas, various gas mixtures, or pure carbon dioxide for arc shielding. Each of these methods has certain advantages and disadvantages for particular applications or materials. Because of this versatility and the speed of the process, GMA welding is widely used by many industries for welding a broad variety of materials, parts, and structures. In fact, nearly every metal-fabricating industry in existence uses the GMA process in some application.

b. Several factors must be considered in applying the GMA process to a specific job. These include the type of material to be welded and its thickness, the desired quality, part design, number and position of welds, and the production rate required. Depending on the interrelation of these factors, semiautomatic, automatic, or spot-type welding may be most desirable. Similarly, the use of one of the shielding gases and process variations will be preferable. Each application should be considered separately to determine the best process variations.

c. Spray transfer is most commonly used in GMA welding. It cannot be used for welding thin material or when welding in the vertical or overhead positions because of the high welding currents and the large molten puddles used. Short-circuiting transfer is therefore used for material less than 1/8 inch thick and when welding in the vertical or overhead positions.

d. The major advantage of spray-transfer GMA welding is that high-quality welds can be produced at high welding speeds. Spray-transfer welds can be made much faster than SMA or GTA welds. Since a flux is not

normally used, there is no chance for the entrapment of slag in the weld metal. The gas shield protects the arc so well that there is very little loss of alloying elements as the metal moves across the arc from the electrode wire to the weld metal. Spray-transfer welding produces some spatter, but it is not excessive. Only minor cleanup is needed after welding to obtain a weld joint with good appearance.

109. THEORY

a. At the time of its development, the gas metal-arc welding process was considered to be fundamentally a high-current-density, small-diameter-filler-wire (0.045 - 3/32 inch diameter) process involving the use of an inert gas for arc shielding. However, the process has since evolved into a much more versatile tool. It can now be operated at lower current density with quite different arc action for certain types of welding. It is possible to use several different types of gases and gas mixtures. Arc stabilizing films or coatings have been applied to certain types of filler wires. Also, fluxes may now be used along with the gas shielding.

b. When using the high-current-density spray-transfer conditions, the arc tends to be steady and quiet. Metal transfer is in the form of a very fine metal droplets and vapor. Figure 33 illustrates the nature of such an arc. Metal transfer occurs within the narrow, incandescent, cone-shaped core of the overall arc column. The wire melts at a rate of from 100 to 800 in./min and metal is transferred at rates from less than 100 to several hundred droplets per second. Because of this high melt-off rate, the filler wire must be fed into the arc by an automatic wire-feeding apparatus.

c. Metal transfer under these conditions is characterized by a magnetic pinch effect and by gas-jet streaming from anode to cathode. Because of the high current density, a coaxial magnetic field is produced at the electrode tip. This exerts a squeezing effect on the end of the wire and causes the molten metal to be pinched off. Vaporization of gas at the electrode tip and electrical forces produce the gas-streaming effect. With these conditions, a deep, papillary penetration along the weld centerline results, as shown in Figure 33.

d. This penetration pattern and the mode of metal transfer are quite different when low current density is used. Penetration is shallower and the papillary stem disappears. The transfer becomes globular and erratic. This may be seen in Figure 34. The degree to which this change in mode of transfer takes place and the current levels at which it occurs vary with different filler metals. Figure 35 shows the amperage levels and wire-feed speeds at which the transfer mode will change with different sizes of aluminum and carbon-steel wires.

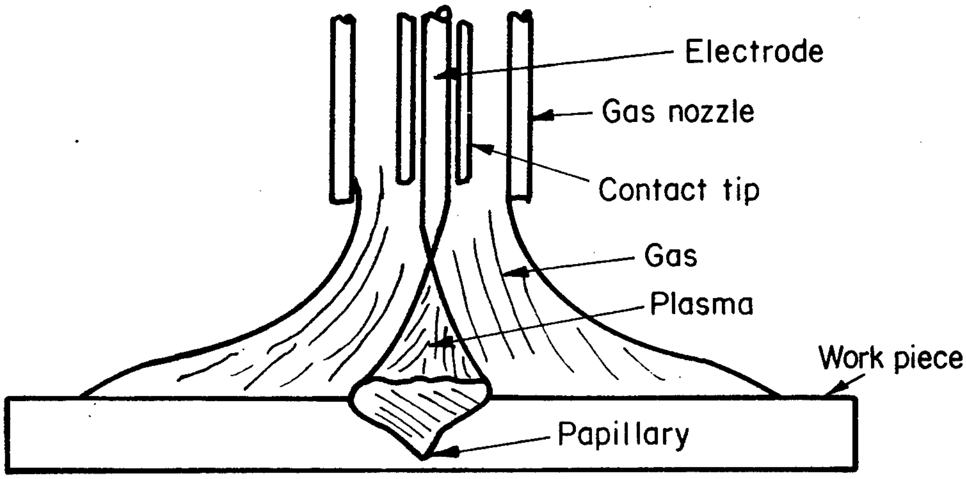


FIGURE 33. ARGON-SHIELDED ARC SHOWING SPRAY-TYPE TRANSFER FROM CONSUMABLE ELECTRODE

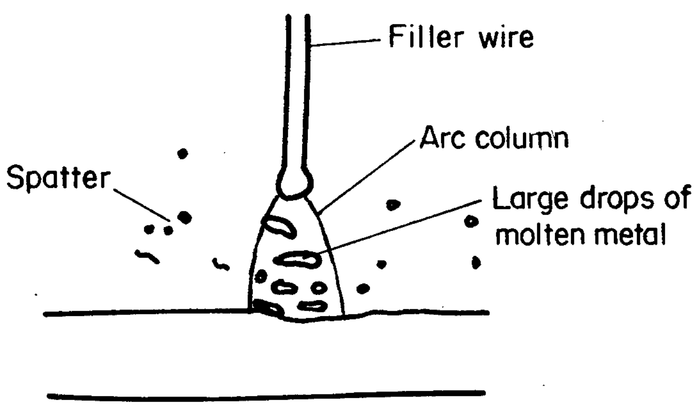


FIGURE 34. GRAVITATIONAL TRANSFER

This mode of transfer may be obtained with straight polarity or low welding currents. It produces low penetration, excess spatter, rough bead shape, and an erratic arc.

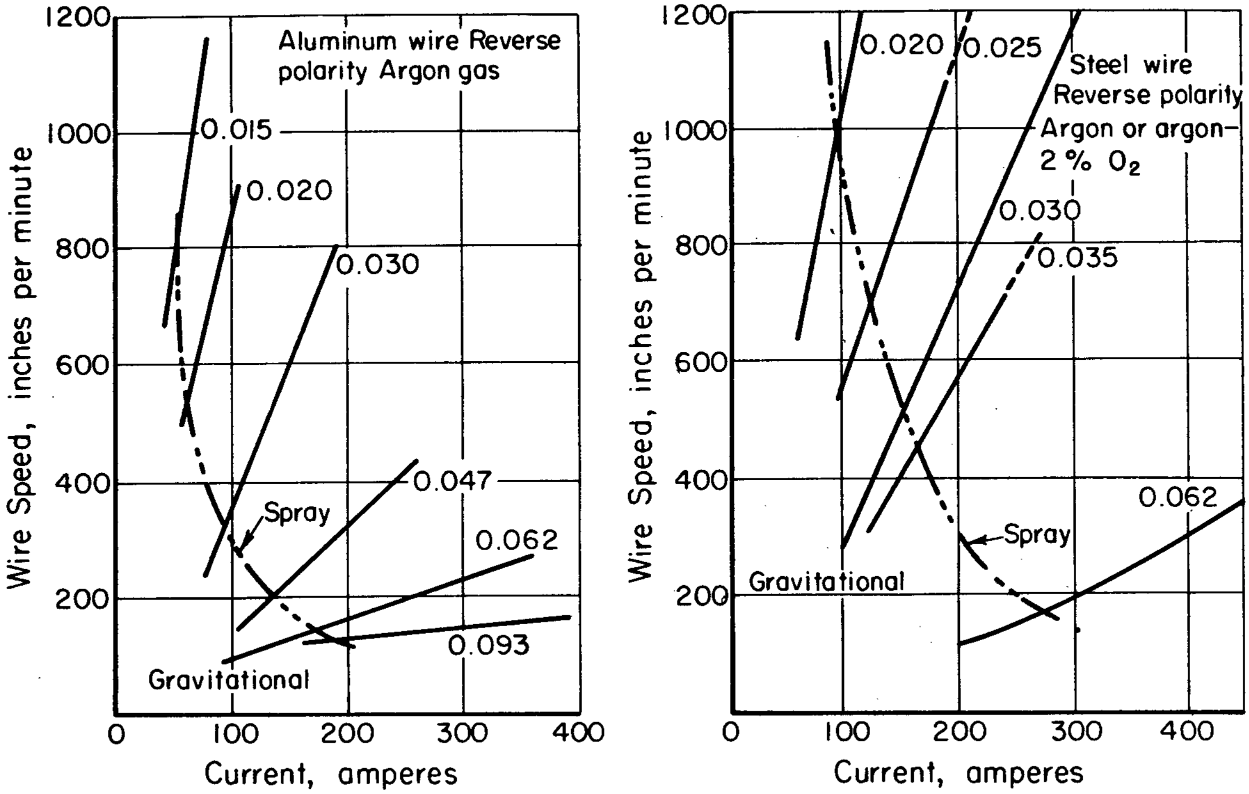


FIGURE 35. BURN-OFF CURVES OF ALUMINUM AND STEEL GAS METAL-ARC ELECTRODES

e. The use of reverse or straight polarity has a marked effect on the arc action on the electrode melt-off rate and on the mode of metal transfer. With straight polarity, the melt-off rate can be much greater than with reverse polarity. The arc is erratic, however, and the gas-streaming (plasma jet) effect is not present. This results in an erratic, globular-type transfer and in poor fusion and poor weld appearance. For this reason, reverse polarity is used almost exclusively with gas metal-arc welding with bare filler wires. Applying a thin, emissive coating on the filler wires, however, changes the metal transfer with a straight-polarity arc to an acceptable spray type. The coatings reduce the electrode burn-off rate to some extent, but in most cases it still remains somewhat faster than with reverse polarity. These coatings have been applied mainly to plain-carbon, low-alloy, and stainless steel filler wires.

f. Because the spray-transfer arc is of relatively high voltage and current density, it is best adapted for welding relatively thick parts. This is true with either reverse or straight polarity. However, the welding range for good spray transfer ranges down to about 1/8 inch.

110. WELDING CURRENT

a. Direct Current, Reverse Polarity. Reverse polarity (electrode positive, workpiece negative) is most generally used with the gas metal-arc process. It provides maximum heat input and produces relatively deep penetration. It also removes oxides from the base metal just ahead of the weld puddle, thereby promoting improved weld quality. Reverse polarity is not satisfactory for welding ferrous metals in pure argon. It causes the arc to wander on the plate and produces a nonuniform weld. It also may cause air to be entrapped in the shielding gas, which can result in weld porosity. This arc instability is due in part to variations in the amount of iron oxide on the plate surface. Addition of a small quantity of oxygen or carbon dioxide to the argon results in a uniformly oxidized surface. This stabilizes the arc cathode within the immediate vicinity of the arc crater, steadies the arc voltage, and promotes a more uniform weld deposit.

b. Direct Current, Straight Polarity. The problems encountered when straight polarity is used with GMA welding have already been discussed to some extent. When bare wire is used, the arc is erratic and poor fusion results. Although the pinch effect is present, the transfer is not of the spray-type, but in the form of large globules. The globules cling to the wire until they become large enough to drop onto the workpiece because of gravitational forces. The condition can be improved by the addition of oxygen to the argon shielding. An addition of 5 percent oxygen will usually stabilize the arc considerably and improve metal transfer; however, it reduces the burn-off rate. A spray-type transfer can also be achieved by addition of metals of the alkali, alkaline-earth, and rare-earth families to the surface of the bare electrode.

c. Alternating Current. Alternating current, when used with gas metal-arc welding, is inherently unstable. This is because the voltage and current both pass through the zero point many times each second, causing the arc to be extinguished each time. An a-c arc cannot be maintained even in a helium atmosphere. In argon it cannot generally be maintained below an open-circuit voltage of 150 volts. With alternating current, the characteristics of both reverse and straight polarity are present, since it is a combination of the two. A stable arc can be attained by coating the electrode wires with dissolved alkali and/or alkaline-earth metals. This tends to stabilize the straight-polarity side of the electrical cycle and has a minimum effect on the reverse-polarity side.

111. EQUIPMENT AND CONTROLS

a. General. The equipment needed for all GMA welding processes include an electrode holder (usually called a welding torch or gun), a mechanism for feeding the filler wire, a power supply, and a set of controls. Filler wire and shielding are also needed.

b. Welding Gun

(1) Both semiautomatic and automatic welding guns are available. There are several designs of semiautomatic guns, but, basically, all have a nozzle for directing the shielding gas around the arc and over the weld puddle. A copper contact tube is located in the nozzle; and the wire passes through it to pick up the welding current. Semiautomatic guns also have a control switch for starting and stopping the welding operation. Some semiautomatic guns have a wire-driving mechanism and are called "pull" guns because they pull the wire through the cable into the gun before it is fed to the arc. In other cases, the wire-drive mechanism is located in the control unit and is driven through a flexible conduit to the welding gun. These guns are less bulky than pull types. In such push-type guns, however, the drive mechanism must be placed relatively close to the welding station, as small-diameter wire tends to buckle when fed long distances. About 12 feet is the maximum distance that filler wire is fed.

(2) One type of semiautomatic welding gun combines both a gun-located pull mechanism and a remote push mechanism for feeding the filler wire (called a "push-pull" wire feed). This equipment was especially designed for welding with very fine wires.

(3) The semiautomatic GMA welding gun may be either air or water cooled. A typical push-type, water-cooled GMA welding gun is shown in Figure 36. Figure 37 shows a typical semiautomatic GMA welding-equipment setup.

(4) Automatic GMA welding guns are mounted directly to the wire-drive mechanism. The combined unit may be in a fixed location, with provision for moving the workpiece underneath the nozzle, or the work may be fixed and the gun-drive mechanism mounted on a movable head. The automatic gun

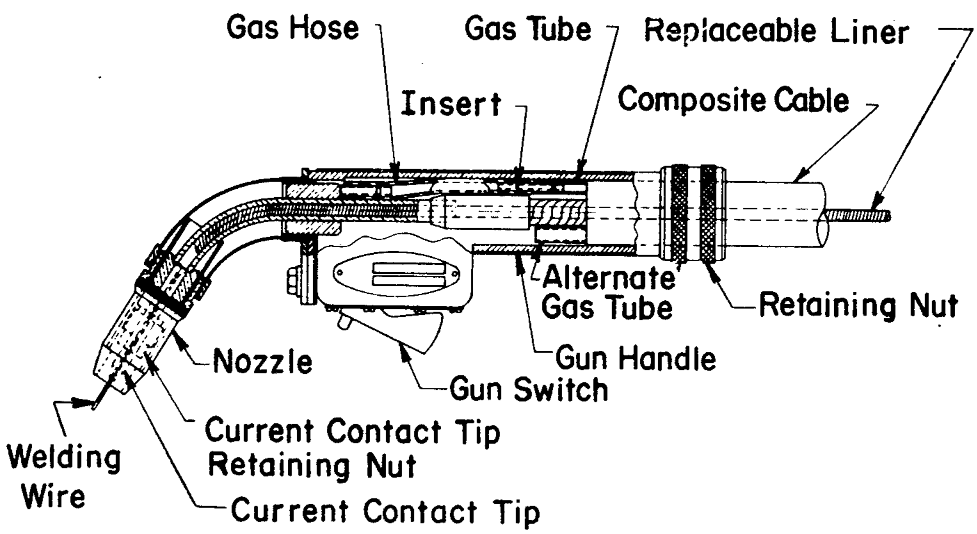


FIGURE 36. TYPICAL MANUAL WATER-COOLED CURVED-NECK TYPE GAS METAL-ARC WELDING ELECTRODE HOLDERS

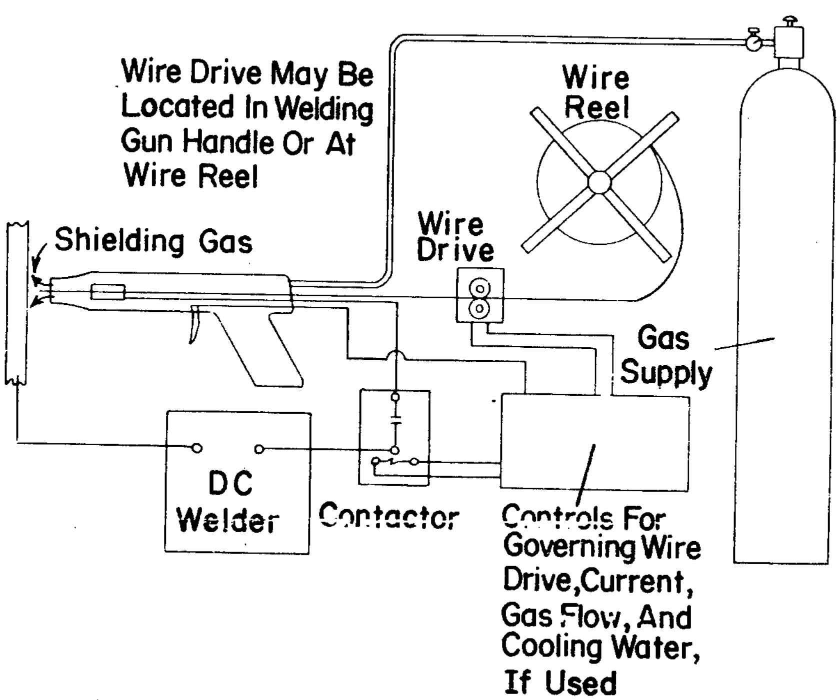


FIGURE 37. SCHEMATIC DIAGRAM OF GAS METAL-ARC WELDING PROCESS

contains the current pickup tube, a water-cooled jacket, and a nozzle for directing the flow of shielding gas. The gun is built more ruggedly than a semiautomatic gun and is designed to operate at higher currents.

c. Wire-Drive Mechanism. The wire-drive mechanism drives the filler wire through the welding gun at a uniform rate. This is done with a set of feed rolls driven by an electric motor (or pair of motors). The speed of the drive motor is adjustable, so that the wire-feed speed can be set to equal the melting rate. If the drive unit is designed to be used with a constant-voltage power source, the speed is set before welding starts and remains constant during welding. If the unit is to be used with a constant-current drooping-voltage power source, the motor speed is varied automatically by an electronic control device.

d. Power Supply

(1) Two types of direct-current power sources are used for spray-transfer gas metal-arc welding, the constant-current type and the constant-voltage type. Motor generator or d-c rectifier power sources of either type may be used.

(2) The constant-current power source is used if the controls and wire-drive mechanism control the arc length by varying the wire-drive speed. In this case, a change in the arc length causes a change in the arc voltage. The control circuit senses this change and varies the wire-feed speed to bring the arc length back to the desired value.

(3) When arc length is controlled through changes in welding current, constant-voltage power supplies are used. The wire-feed speed is constant. Changes in arc length cause automatic changes in welding current, which compensate for the arc-length change. If the arc length becomes shorter, the welding current automatically increases. This causes the wire to melt faster and the arc length to increase. The reverse happens if the arc is lengthened during welding.

e. Controls

(1) The control unit performs several operations. It starts and stops the wire-feed motor, shielding-gas flow, and cooling-water flow. Appropriate delay devices are incorporated which

start the shielding gas and water flow a few seconds before the arc starts and maintains the flow for a brief interval after welding stops. Burnback of the wire at the end of the weld is regulated so that the end of the wire will not freeze in the weld pool. A control to adjust the wire-feed speed, arc length, or welding current may be included in the unit. For semiautomatic welding, the control unit is usually mounted with the wire-drive mechanism and filler-wire holder. A remote control may be placed at the welding station to allow the welder to control the operation from his position. Automatic welding control units are usually mounted alongside the welding gun.

(2) The wire-feed speed must be very closely maintained for gas metal-arc welding with a constant-current power supply. If it is not, the arc may either shorten or lengthen. In the first case, the wire may stick to the work; in the second, it may burn back to the guide tube. To prevent such happenings, wire-feed speed is usually controlled by a governor.

112. ELECTRODE FILLER WIRE

a. Metal transfer in GMA welding is affected by the composition and surface treatment of the electrode filler wire used. The wire diameter and wire extension from the contact tube also affect the type of transfer. Gas metal-arc filler wires have small diameters compared to those used for other types of welding. They may vary from 0.020 inch to 1/8 inch in diameter, but 1/16 inch is about average. Because of the high burn-off rates of these wires mentioned earlier, they are provided in long, continuous strands. They are tempered so that they feed smoothly and continuously through the welding apparatus. Steel wires often have a light flash coat of copper to prevent their rusting and to improve the electrical contact. For best welding results, the wire should be protected and kept clean.

b. The composition of GMA filler wire is similar or identical to those used for other bare-wire welding processes. Generally, the composition is as near that of the base material as is practicable. In some cases, however, it must be of an entirely different composition. For example, manganese bronze is most satisfactorily welded with either an aluminum-bronze or a copper-manganese-nickel-aluminum-alloy filler wire. Some very high-strength aluminum and steel alloys are welded with filler wires having compositions different from the base metal to prevent weld cracking.

c. Filler wires for gas metal-arc welding nearly always contain deoxidizers or scavenging agents. These additives prevent porosity and damage to the mechanical properties of the weld from oxygen, nitrogen, or hydrogen. For steel filler wires, manganese, silicon, and aluminum are most frequently used as deoxidizers. In nickel-alloy wires, titanium and silicon are generally used. Titanium, silicon, and phosphorus may be used for copper alloys. Titanium, zirconium, aluminum, and magnesium filler wires do not contain deoxidizers because the metals are so reactive themselves that nothing else can serve the purpose. Thus, it is necessary to weld these metals with oxygen-free inert gas and with the very best possible arc shielding. Titanium and zirconium may require that welding be done in a closed chamber filled with protective gas.

d. Table XVII shows the filler metal generally recommended for welding various metals and alloys. The table is based on current practice, but does not mean that these are the only possible choices.

113. SHIELDING GASES

a. Functions. Shielding gases in the gas metal-arc process are used primarily to protect the molten metal from oxidation and contamination. Other factors must be considered, however, in selecting the right gas for a particular application. Shielding gas can influence arc and metal-transfer characteristics, weld penetration, width of fusion zone, surface-shape patterns, welding speed, and undercut tendency. Inert gases such as argon and helium provide the necessary shielding because they do not form compounds with any other substance and are insoluble in molten metal. When used for welding ferrous metals, arc action may be erratic and the metal transfer globular. It is therefore necessary to add controlled quantities of reactive gases to achieve good arc action and metal transfer with these materials. The principal gases and mixtures used for GMA welding are shown in Table XVIII together with their characteristics and principal uses.

b. Argon, Helium, and Argon-Helium Mixtures.

(1) Argon and helium are most frequently used when a completely inert-gas shield is desired for gas metal-arc welding. They are equally inert, but each has other characteristics that make it, or a mixture of the two, best for welding certain materials. Helium is preferable for welding thick materials, especially those with high heat conductivity such as copper, aluminum, and some copper-base alloys. This is because of the higher ionization potential of helium, which results in greater weld heat at a given amperage (see Figure 38). Argon

TABLE XVII. GENERALLY RECOMMENDED FILLER METALS AND SHIELDING GASES FOR GAS METAL-ARC WELDING VARIOUS BASE METALS

Base Metal Type	Shielding Gas Composition	Specific Alloy to be Welded	Filler Metal Type, electrode	Elect. Dia., in.	Current Ranges, amps, dcrp	Remarks
Aluminum and its alloys	Pure argon or helium-argon (75-25)	1100	1100 or 4043	0.030	50-175	ASTM designations
		2219	4145 or 2319	0.045	90-250	
		3003,3004	2319	1/16	160-350	
		5050	4043	3/32	225-400	
		5052	4043 or 5554	1/8	350-475	
		5154,5254	5554 or 5154			
		5083,5084,5456	5554 or 5154			
		6061	5556 or 5356			
		7039	4043 or 5556			
			5556,5356 or 5183			
Magnesium alloys	Pure argon	AZ31B,61A,81A	AZ61A	0.045	220-280	ASTM designations
		ZE10XA		1/16	240-390	
		ZK20XA		3/32	330-420	
		AZ31B,61A,63A	AZ92A			
		80A,81A,91C,92A				
		AM80A,100A				
		ZE10XA				
		XK20XA	AZ63A			
		AZ63A				
Copper	Helium-argon mixture (75-25) Pure argon on thin sections	Deoxidized copper	Deoxidized copper Silicon-0.25% Tin-0.75% Mn-0.15%	1/16	300-470	
Copper-Nickel alloy	Pure argon	Cu-Ni alloy: 70-30 90-10	Titanium deoxidized 70-30 Cu-Ni 70-30 or 90-10	1/16	250-300	
Bronzes	Pure argon	Manganese bronze	Aluminum bronze	1/16	225-300	Aluminum bronze wire may be solid alloy or stranded
		Aluminum bronze	Aluminum bronze	5/64	275-350	
		Nickel-aluminum bronze	Aluminum bronze			
	Argon + 5% O_2	Tin bronze	Phosphor bronze			

TABLE XVII. GENERALLY RECOMMENDED FILLER METALS AND SHIELDING GASES FOR GAS METAL-ARC WELDING VARIOUS BASE METALS (CONTINUED)

Base Metal Type	Shielding Gas Composition	Specific Alloy to be Welded	Filler Metal Type, electrode	Elect. Dia., in.	Current Ranges, amps, dcrp	Remarks
Nickel and nickel alloys	Helium-argon mixture (75-25) or pure argon	Nickel Nickel-copper (Monel) Nicke-Chromium (Inconel)	Similar to base metal, titanium deoxidized (see supplier)	0.035 0.045 1/16	100-150 150-260 100-400	
Plain-low carbon steel	CO_2; argon + 10 to 30% CO_2; or agron + 2 to 5% O_2	Hot or cold rolled sheet or plate ASTM A7,A36 A285,A373 or equivalent	Deoxidized plain carbon steel	0.030 0.035 0.045 1/16 5/64	50-160 75-250 100-350 300-450 350-500	Straight polarity with special wire
Low-alloy carbon steel	Argon + 1-2% O_2 or argon + 10-30% CO_2	Hot or cold rolled sheet or plate of various grades	Deoxidized low alloy steel	0.030 0.035 0.045 1/16	50-160 75-250 100-350 300-450	
Stainless steel	Argon + 1-5% O_2	302,304 321,347 309,310 316, etc.	Electrode to match base alloy	0.030 0.035 0.045 1/16	75-150 100-160 140-310 280-350	AISI designations

TABLE XVIII. SHIELDING GASES AND GAS MIXTURES USED FOR GAS METAL-ARC WELDING

No.	Shielding Gas	Chemical Behavior	Uses and Usage Notes
1	Argon	Inert	Welding virtually all metals except steel.
2	Helium	Inert	Al and Cu alloys for greater heat and to minimize porosity.
3	Ar & Hel (20-80 to 50-50%)	Inert	Al and Cu alloys for greater heat and to minimize porosity, but with quieter, more readily controlled arc action.
4	Ar & Cl (Trace Cl)	Essentially Inert	Al alloys, to minimize porosity.
5	N_2	Reducing	On Cu, very powerful arc.
6	Ar + 25-30% N_2	Reducing	On Cu, powerful but smoother operating, more readily controlled arc than with N_2.
7	Ar + 1-2% O_2	Oxidizing	Stainless and alloy steels, also for some deoxidized copper alloys.
8	Ar + 3-5% O_2	Oxidizing	Plain carbon, alloy and stainless steels (generally requires highly deoxidized wire).
9	Ar + 5-10% O_2	Oxidizing	Various steels, deoxidized wire.
10	Ar + 20-30% CO_2	Oxidizing	Various steels, chiefly with short-circuiting arc.
11	Ar + 5% O_2 + 15% CO_2	Oxidizing	Various steels, deoxidized wire, used chiefly in Europe.
12	CO_2	Oxidizing	Plain-carbon and low-alloy steels, deoxidized wire essential.
13	CO_2 + 3-10% O_2	Oxidizing	Various steels, deoxidized wire, used chiefly in Europe.
14	CO_2 + 20% O_2	Oxidizing	Steels, favored and chiefly used in Japan.

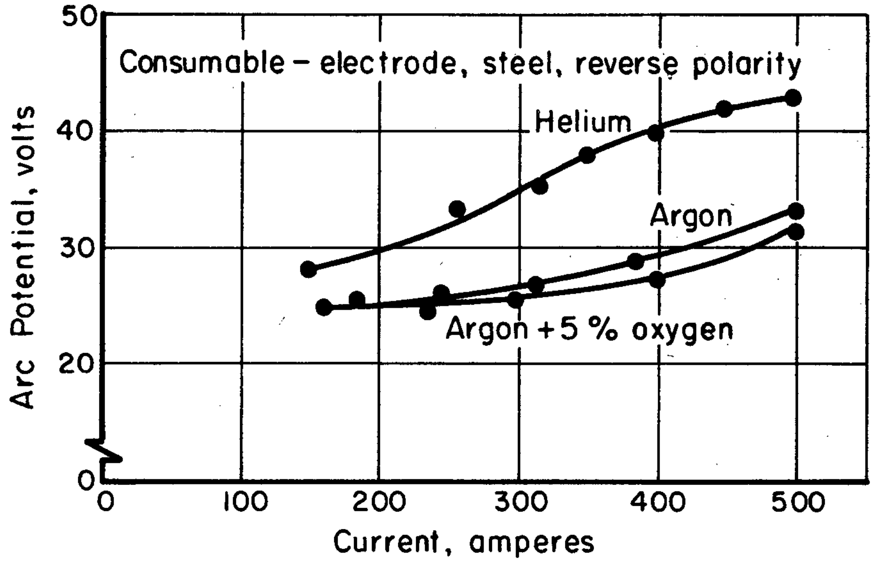


FIGURE 38. ARC CHARACTERISTICS OF VARIOUS GASES

is more suitable for use with lighter-gage materials and materials of lower heat conductivity because it produces lower weld heat.

(2) Argon, being heavier than helium, does not require as high a flow rate to provide the same amount of shielding. Helium tends to rise and disperse from the weld region because of its lightness. For the same reason, an argon-helium mixture will require a higher flow rate than argon alone.

(3) Argon generally produces a spray transfer at lower current levels, and to a greater extent than does helium. With certain types of filler wire, spray transfer is practically impossible with helium. Spray transfer is not always attainable even with argon, and this is the main reason for adding oxygen or carbon dioxide for welding some materials. The characteristics of metal transfer have a great influence on weld penetration and bead shape. Spray transfer results in a deeper penetration at the weld centerline and shallower at the edges. Gravitational transfer will produce a broader, shallow penetration. Figure 39 shows the penetration pattern obtained with various shielding gases. When argon is used alone for plain-carbon and most alloy steels, there is a tendency for uneveness and undercut to occur along the weld edges. This can also be seen in Figure 39 and is confined to reverse-polarity-type operation.

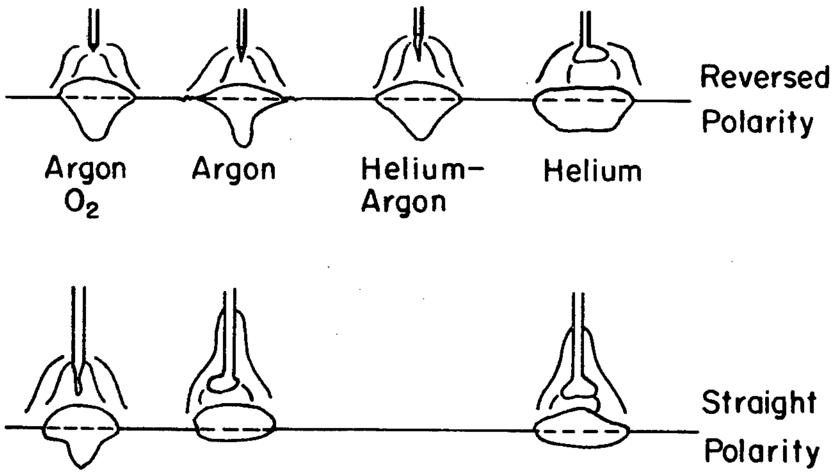


FIGURE 39. BEAD CONTOUR AND PENETRATION PATTERNS FOR VARIOUS SHIELDING GASES WHEN GAS-METAL-ARC WELDING

c. Reactive Gas Additions to Argon and Helium

(1) There is a tendency for erratic globular transfer and for weld undercut when pure argon is used for shielding in certain applications, as mentioned in the previous paragraph. This is true particularly when ferrous metals are being welded. Adding oxygen or carbon dioxide to the inert gas tends to stabilize the arc, promote favorable metal transfer, and minimize spatter. As a result, the penetration pattern is improved, and undercutting is reduced or eliminated. The changes produced by the addition of oxygen are illustrated in Figure 39.

(2) Oxygen or carbon dioxide are usually added only to argon; they are rarely added to helium or a helium-argon mixture. The amount of reactive gas required to produce the desired effects is quite small. As little as a half percent of oxygen will produce noticeable change. One to five percent additions are more common, however. (For short-circuiting-type transfer, as much as 20 to 30 percent carbon dioxide may be added to argon.)

(3) Adding oxygen or carbon dioxide to an inert gas causes the shielding gas to become oxidizing. This in turn may cause porosity in some ferrous metals. In this case, a filler wire containing suitable deoxidizers should be used. The presence of oxygen in the shielding gas can also cause some loss of

certain alloying elements, such as chromium, vanadium, aluminum, titanium, manganese, and silicon. Again, the addition of a deoxidizer to the filler wire is necessary.

(4) By adding a small percentage of chlorine to argon or helium shielding gas, the tendency for porosity in some materials may be reduced. This is especially true of aluminum. Chlorine is most effective in this case when it is introduced separately through the contact tube bore of the welding torch. This is not a widely used application because chlorine is both poisonous and highly corrosive, and extreme caution is necessary.

d. Carbon Dioxide. Pure carbon dioxide has become widely used as a shielding gas for GMA welding of steels. It allows higher welding speed, better penetration, good mechanical properties, and costs less than the inert gases. The chief drawback in the use of carbon dioxide is the less-steady-arc characteristics and considerable weld-metal-spatter losses. The spatter can be kept at a minimum by maintaining a very short, uniform arc length. Consistently sound welds can be produced using carbon dioxide shielding, provided a filler wire having the proper deoxidizing additives is used.

114. GAS DENSITY AND FLOW RATES

Density is the chief factor determining how effective a gas is for arc shielding. The lower the density of a gas the higher will be the flow rate required for equal arc protection. The flow rates, however, are not in proportion to the densities. Helium, with about one-tenth the density of argon, requires only twice the flow for equal protection. Table XIX shows typical flow rates recommended for various materials.

115. ARC-VOLTAGE CHARACTERISTICS

The arc-voltage characteristics of shielding gases differ. So, too, do the arc voltages that are best for welding in different positions and with different process variations. Arc voltage may also differ with different materials. The arc voltage always increases when the arc is lengthened and decreases when the arc is shortened. For normal welding production, there are no set values of arc voltage that are always best. Values will depend on factors such as material thickness, type of joint, position of welding, wire size, process details, gas composition, and type of weld. Table XX shows some typical arc voltages for welding of different materials with different shielding gases. For any particular application, trial runs should be made and the arc voltage adjusted to achieve best results.

TABLE XIX. TYPICAL SHIELDING GAS FLOW RATES* FOR GAS METAL-ARC WELDING VARIOUS MATERIALS

Materials	Spray-Type Arc-- 1/16 in. dia filler wire					Short Circuiting Arc-- 0.035 dia filler wire			
	Argon	Helium	Argon-Helium (25-75)	Argon-Oxygen (1-5% O_2)	CO_2	Argon	Argon-Oxygen (1-5% O_2)	Argon-CO_2 (75-25)	CO_2
Aluminum	50	100	80	--	--	35	--	--	--
Magnesium	50	100	80	--	--	35	--	--	--
Plain C Steel	--	--	--	40	40	25	25	25	35
Low alloy steel	--	--	--	40	40	25	25	25	35
Stainless steel	40	--	--	40	--	25	25	--	35
Nickel	50	100	80	--	--	35	--	--	--
Ni-Cu alloy	50	100	80	--	--	35	--	--	--
Ni-Cr-Fe alloy	50	100	80	--	--	35	--	--	--
Copper	50	100	80	--	--	30	--	--	--
Cu-Ni alloy (70-30)	50	100	80	--	--	30	--	--	--
Si bronze	40	80	60	--	--	25	25	--	--
Al bronze	50	100	80	--	--	35	--	--	--
Phos. bronze	40	80	60	40	--	25	25	--	--

*All rates are in cubic feet per hour and are plus or minus 40%. The lower rates would be most suitable for indoor work and moderate amperage welding. The higher rates would be more suitable for high current, maximum speed and outdoor welding.

116. SHIELDING GASES FOR WELD CLADDING.

An important application of GMA welding is the deposition of cladding on metals for corrosion protection. Pure argon or argon-oxygen mixtures are most generally used for cladding operations, although argon-helium mixtures have been used. Helium or helium-argon mixtures result in a higher weld penetration and increase the amount of dilution of the deposited weld metal by the base metal. Since dilution should be minimized in weld cladding, the argon and argon-oxygen mixtures are preferable. The argon-helium mixtures may be useful for high-conductivity materials such as copper or copper-base alloys where high heat inputs are necessary to assure adequate fusion.

117. QUALITY ASSURANCE

a. There are many variables in the gas metal-arc process that can affect weld quality. These have been discussed earlier as affecting the wire melting rate and arc stability and consequently weld penetration. They include polarity, shielding gas, welding current, arc length, electrode diameter and extension, arc manipulation, travel speed, and joint design.

b. Frequently, the problems encountered in welding may be traced to equipment failures. Good equipment-maintenance procedures are a definite requirement if quality welds are to be consistently produced. Proper maintenance of welding-current leads are also an important safety precaution, as discussed in Chapter 4.

c. Proper welding procedures are also important, as will be discussed in Chapter 11. The proper combination of welding current and voltage and travel speed, as well as qualified welding personnel, are required to produce high-quality welds with the GMA process.

d. Of particular importance is the cleanliness of the wire surface. Because the diameter of the wire is quite small, there is a high surface-to-volume ratio. Therefore, any foreign matter on the wire will be in a high proportion to the total amount of filler metal. Although all materials are sensitive in some degree to such foreign matter it is particularly critical when welding such materials as titanium, zirconium, aluminum, magnesium, and some nickel alloys.

Section II. SHORT-CIRCUITING METAL TRANSFER

118. DEFINITION

a. Short-circuiting, gas metal-arc welding is a relatively new extension of the gas metal-arc process. The major difference between short circuit and spray transfer is the manner in which the molten metal is transferred from the end of the filler wire to the weld puddle. With the short-circuiting process, metal transfer occurs during repetitive short circuits through contact of the molten electrode with the weld puddle, rather than by droplet transfer through the arc column (Figure 4, Chapter 2). Otherwise the processes are similar. The electrode wire is fed automatically through the welding gun from a coil to the arc. The arc, weld puddle, and the end of the filler wire are shielded from the atmosphere by an inert gas, a reactive gas, or a combination of the two.

b. Short-circuiting transfer is particularly well-suited for welding thin sections because of the relatively low heat input associated with this type of transfer.

119. IMPORTANCE AND USES

a. The short-circuiting process is adaptable to most metals, provided the wire has good burn-off characteristics and the correct shielding gas and power supply are used. It is widely used for welding thin materials in all positions and has gained some use for vertical and overhead welding of heavier gage materials. The process is most widely used with carbon and low-alloy steels. It is used to a lesser degree with stainless steel and light-gage aluminum.

b. Generally, welds made with the short-circuiting GMA process are of slightly poorer quality than GTA welds. However, the short-circuiting process offers much higher welding speeds. Therefore, the process can be used to advantage in applications where very high-quality welds are not essential.

120. THEORY

a. Welding with a short-circuiting arc employs direct-current reverse polarity. The current level is generally low, ranging from 50 to 225 amperes, with voltages of 12 to 22 volts. The process uses small-diameter wires, the most popular sizes being 0.030, 0.035, and 0.045 inch diameters. Table XX shows the arc voltages required with a given shielding gas to effect short-circuiting transfer when various materials are being welded.

TABLE XX. TYPICAL ARC VOLTAGES FOR GAS METAL-ARC WELDING VARIOUS MATERIALS

Materials	Spray-Type Arc-- 1/16 in. dia filler wire					Short Circuiting Arc-- 0.035 dia filler wire			
	Argon	Helium	Argon-Helium (25-75)	Argon-Oxygen (1-5% O_2)	CO_2	Argon	Argon-Oxygen (1-5% O_2)	Argon-CO_2 (75-25)	CO_2
Aluminum	25	30	29	--	--	19	--	--	--
Magnesium	27	31	30	--	--	19	--	--	--
Plain C steel	--	--	--	28	30	17	18	19	20
Low alloy steel	--	--	--	28	30	17	18	19	20
Stainless steel	24	--	--	26	--	18	19	21	--
Nickel	26	30	28	--	--	22	--	--	--
Ni-Cu alloy	26	30	28	--	--	22	--	--	--
Ni-Cr-Fe alloy	26	30	28	--	--	22	--	--	--
Copper	30	36	33	--	--	24	22	--	--
Cu-Ni alloy	28	32	30	--	--	23	--	--	--
Si bronze	28	32	30	28	--	23	--	--	--
Al bronze	28	32	30	--	--	23	--	--	--
Phos. bronze	28	32	30	28	--	23	--	--	--

b. The short-circuiting arc is characterized by the frequent shorting of the wire to the work. The arc is extinguished at a steady rate of from 20 to over 200 times a second. All metal transfer takes place during these periods. The arc is stable with low energy and heat input. Because of the low heat input, there is little distortion and few metallurgical effects. The complete metal-transfer cycle, including re-establishment of the arc, is shown in Figure 40. Each short circuit should create a definite, but controlled, current surge sufficient to recreate the arc without undesirable metal spatter.

c. The shielding gases used for the free-flight transfer GMA process can also be used for the short-circuiting GMA process. For thin aluminum, pure argon or helium, or mixtures of the two, are used. Either carbon dioxide, a carbon dioxide-argon mixture, or an argon-oxygen mixture may be used with carbon and low-alloy steels. Because of the smaller weld puddle, the shielding-gas flow rate is generally less than with spray transfer: typically 15 to 25 cubic feet per hour. Typical cross sections of carbon-steel fillet welds made using three different shielding gases with the short-circuiting process are shown in Figure 41. Table XVIII in Paragraph 113a may be referred to for other shielding-gas mixtures.

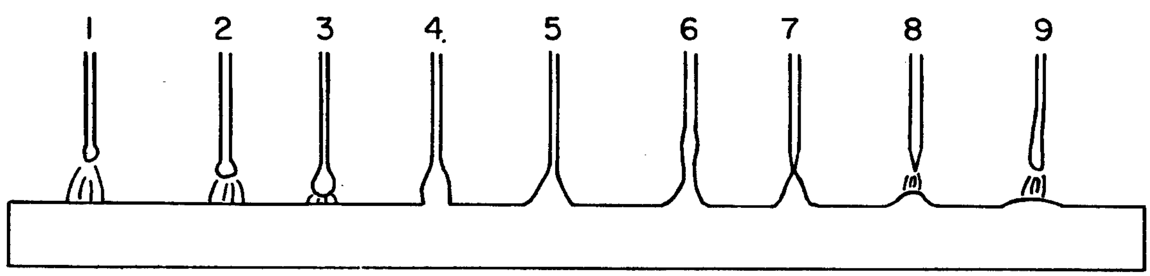


FIGURE 40. STEPS IN SHORT-CIRCUITING METAL TRANSFER

d. Short-circuiting metal transfer uses filler wires of the same composition as those used with spray transfer. The major difference is that a smaller diameter wire is used with short-circuiting transfer as discussed earlier.

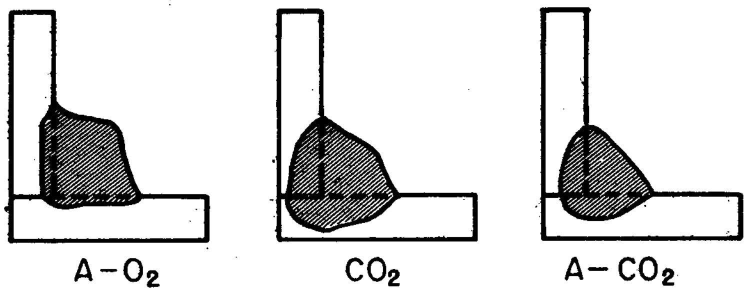


FIGURE 41. CROSS-SECTION SKETCHES OF FILLET WELDS MADE WITH DIFFERENT SHIELDING GASES AND THE SHORT-CIRCUITING ARC TECHNIQUE

121. EQUIPMENT

a. Short-circuiting gas metal-arc welding utilizes the same equipment as does spray transfer. Constant-potential welding machines are used to get full advantage of the short-circuiting characteristics. Welding machines designed specifically for the process are available. These direct-current welding power supplies are designed to operate between 200 and 300 amperes at constant voltage. The machines should have a built-in slope control or an adjustable inductance for controlling the momentary current surges during the short-circuiting period of the metal transfer cycle.

b. The wire-feed system should be of the constant-feed design, using either mechanical- or electronic-type speed controls. A wire-feed speed range of 50 to 800 inches per minute is adequate for nearly all applications.

c. The welding torch may be either air or water cooled and may have either a straight or curved nozzle. The curved, or blowpipe, nozzle design is most popular.

d. The controls required will depend on whether the operation is semiautomatic or automatic. In either case, they are the same as those used for spray transfer.

e. The factors affecting quality with short-circuiting transfer are the same as those in the spray-transfer process.

Section III. GMA SPOT WELDING

122. DEFINITION

a. Gas metal-arc spot welding (GMA) is the same in most regards as GTA spot welding and does not require a lengthy separate discussion. The discussion of the latter process in Section II of Chapter 5 is generally applicable to GMA spot welding. The following differences in the GMA process should be noted:

(1) The arc is struck between a consumable wire electrode rather than a nonconsumable electrode.

(2) An inert gas is not always used; for most steel-welding applications, carbon dioxide shielding is used.

(3) Standard GMA welding guns are used with a special nozzle adapter for spot-welding applications.

(4) Direct-current reverse polarity is usually used rather than straight polarity.

123. IMPORTANCE AND USES

GMA spot welding may be used for the same applications as the GTA spot-welding process, but each has inherent advantages for particular applications. Because of the addition of filler wire, the gas metal-arc spot weld leaves a raised spot. Thus, where surface appearance is important, gas tungsten-arc is the better process. However, where filler metal is required for crack-sensitive materials, or for other reasons, the GMA process is preferable.

124. THEORY

a. As mentioned earlier, the major difference between GMA and GTA spot welding is the consumable wire electrode used in the former. Because of this electrode, the control circuit for GMA must include a wire-feed timer to accurately control the amount of wire required to make a spot weld.

b. GMA spot welding uses the same shielding gases, or mixtures of gases, as are recommended for normal GMA welding. Likewise, direct-current, reverse polarity is usually used for GMA spot welding.

125. EQUIPMENT AND CONTROLS

The equipment and controls used for GMA spot welding are the same as those used for normal GMA welding with the exception of the welding hand gun or torch nozzle, and the control circuit. The standard GMA welding hand gun is adapted to spot welding by addition of a special nozzle adapter which rests against the work and properly spaces the end of the contact tube from the work surface. A special control is required to regulate the arc time and the speed of the wire being fed into the arc.

126. QUALITY ASSURANCE

The quality of welds produced by GMA spot welding depends on following good welding procedures and practices. The practices and procedures listed under quality assurance for GMA welding, and GTA spot welding, are applicable here.

Section IV. PULSED-ARC GMA PROCESS

127. DEFINITION

a. Pulsed-arc GMA welding is a modification of GMA welding that is used to obtain spray-type transfer with lower welding currents. Since the gravitational mode of metal transfer, usually obtained at currents below the normal spray-transfer range, is generally deficient, the GMA process was restricted in its applicability. The development of the short-circuiting GMA process partially filled this deficiency. It permitted welding with very low heat inputs. The pulsed-arc GMA process is a further step in filling the void. It provides a higher ratio of heat input to metal deposition than the short-circuiting process and operates at heat inputs between the spray-transfer and short-circuit-transfer range.

128. IMPORTANCE AND USES

a. Pulsed-arc GMA is a relatively new process and has received quite limited use commercially. A generalized comparison to short-circuiting arc processes may give some idea of its potential use. The minimum heat input obtainable is about the same for the two processes, but pulsed-arc can work with maximum heat inputs in the globular-transfer range, while short-circuiting transfer cannot. A higher ratio of heat input to metal deposition can be achieved with pulsed-spray. Pulsed arc is also practically spatter free and permits the use of a completely inert-gas shield. The heat-input range of pulsed arc overlaps the ranges

available with short-circuiting and spray-transfer processes. In the lower heat-input range, pulsed-spray has the advantages of the continuous projected free-flight transfer process. The pulsed-arc process, therefore, is very useful in applications requiring low heat input, such as for out-of-position welding of thin materials. In areas where the short-circuiting process is properly applicable, it is more economical, and the pulsed-arc process will not find application. One reason for this is that, unlike short-circuiting transfer, it will not tolerate large variations in joint fitup.

b. Root penetration in pulsed-arc welds is nearly as uniform as that in gas-tungsten-arc welds. Thus, in some cases it may be possible to weld without backing.

c. The possible uses of pulsed-arc welding in relation to specific materials are discussed in the following paragraphs.

(1) Mild and Low-Alloy Steels. The pulsed-spray process has the ability to produce high-quality welds with controlled penetration in mild and low-alloy steels. This facility should prove useful for out-of-position applications, such as pipe butt welding, where high quality is of prime importance. The process may also prove useful for welding sheet steels just below the lower heat-input limit of free-flight transfer.

(2) Aluminum. The pulsed-arc process allows the use of larger diameter wires. With the increased diameter, the surface-to-volume ratio of the wire is decreased. Thus, weld-metal porosity due to hydrogen and oxygen pickup on the wire surfaces is also decreased. This makes pulsed-arc a very attractive process for welding aluminum. The larger diameter wire also offers the advantage of lower initial cost and allows the use of push-type wire feeders.

129. THEORY

a. As stated earlier, the pulsed-arc process is an extension of projected free-flight transfer welding at a much lower current level. The pulsing current used has its peak value in the free-flight transfer current range and its minimum value in the gravitational-transfer current range.

b. With an inert, or nearly inert, shielding gas, the gravitational-transfer current range extends from the minimum current at which the electrode will melt to the transition current. Transition current is the

point at which metal transfer changes from gravitational to projected (see Figures 42 and 43). Gravitational transfer is very erratic and cannot be used out of position.

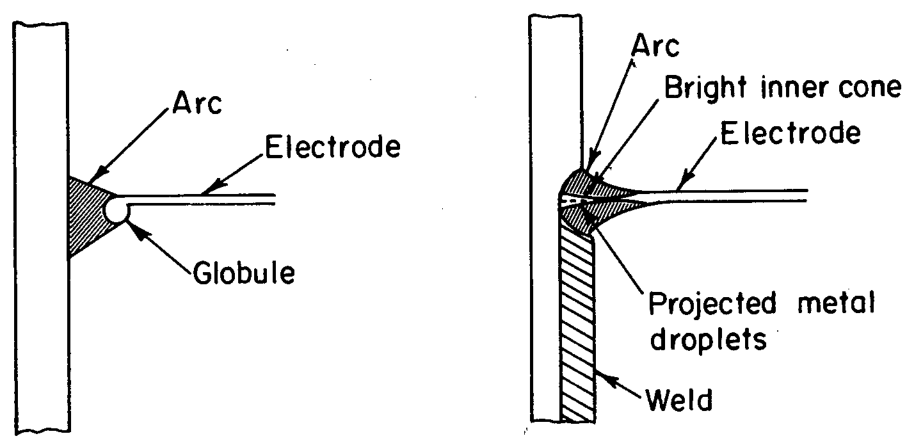


FIGURE 42. SITUATION WHEN AN ARC TRANSFERRING METAL BY DIFFERING MODES IS APPLIED IN THE VERTICAL WELDING POSITION

c. Projected (spray) transfer results when welding currents higher than the transition current are used. The spray arc is very stable and is concentrated so that it can be directed wherever desired. Metal can be transferred out of position because the axial force producing transfer is stronger than gravity. However, in actual practice, out-of-position welding is still not practical. The high current needed to induce projected free-flight transfer creates a very high heat input and results in a weld puddle too fluid for out-of-position welding. The same factors explain the burn-through obtained when a weld on thin material is attempted. Thus, the spray-transfer process is very good for flat-position welding but quite limited in its use for other positions and thin materials.

d. In pulsed-arc transfer, the current is pulsed back and forth between the spray-transfer and gravitational-transfer current ranges. This is illustrated in Figure 44. In this figure, Power Source A puts out a current in the gravitational-transfer range and Power Source B puts out current in the projected transfer range. On the right, the two outputs are combined to

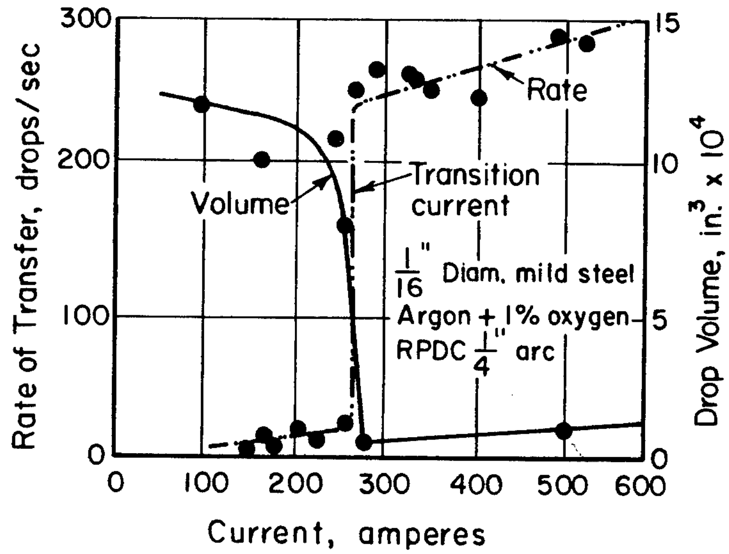


FIGURE 43. EFFECT OF CURRENT ON THE SIZE AND FREQUENCY OF DROPS TRANSFERRED IN AN ARC SHIELDED BY PREDOMINANTLY INERT GAS

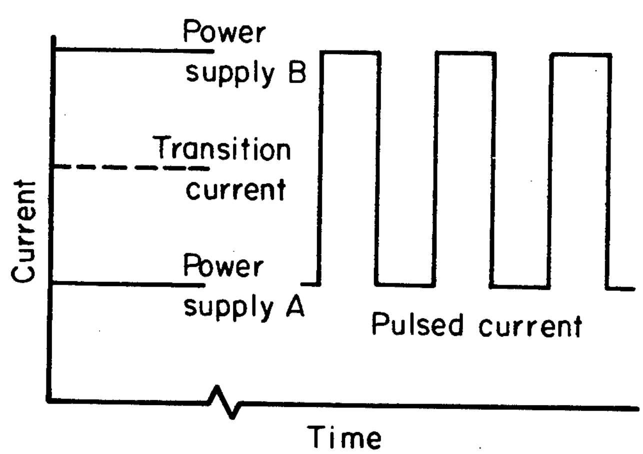


FIGURE 44. ILLUSTRATION OF HOW A SWITCHING SYSTEM CAN CONVERT TWO STEADY-STATE D-C OUTPUT CURRENTS INTO A SIMPLE PULSING-CURRENT OUTPUT WAVE FORM

produce a simple pulsed output by electrically switching back and forth between them. This pulsing does not allow sufficient time for gravitational transfer to occur, but there is more than sufficient time for projected transfer. Thus, transfer is restricted to the projected mode. The process offers all the advantages of the spray-transfer process at lower average current levels. These range from the minimum possible with continuous spray transfer down to values low in the gravitational range.

130. EQUIPMENT

a. Power Source

(1) The power source for pulsed-arc welding must insure that the time period between consecutive pulses is less than that needed for gravitational transfer to occur. A 60-cycles-per-second power line produces a period between pulses short enough to suppress gravitational transfer at all current levels. At the same time, the pulse duration is sufficient to ensure that projected free-flight transfer will occur.

(2) A typical power source for pulsed-arc welding combines a three-phase, full-wave transformer-rectifier power supply with a single-phase, half-wave pulse unit, as shown in Figure 45. Both are of the constant-potential type. The single-phase power supply is called the "pulsing" unit; the three-phase power supply is called the "background" unit. The units are connected in parallel, but switch in operation. Figure 46 shows the current output-wave form and metal-transfer sequence.

(3) The varying output voltage of the pulsing unit causes the units to switch back and forth in operation. Two reactors, shown as A and B in Figure 45, are used. Reactor A performs a commutation function. It momentarily sustains the welding current when pulse voltage drops below the background voltage. This gives the background unit time to respond to the demand for current. Reactor B prevents undesirable arc outages at low background-current levels.

(4) The pulsed-current power source is operated similarly to conventional constant-potential sources. With the arc off, the pulse peak voltage is set by means of the handwheel. This value depends on the electrode type and diameter and

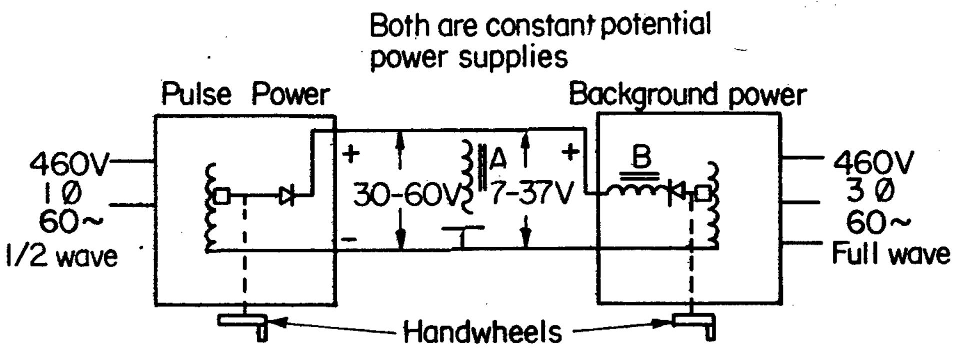


FIGURE 45. BLOCK DIAGRAM OF THE ESSENTIAL FEATURES OF A PULSED-CURRENT POWER SUPPLY

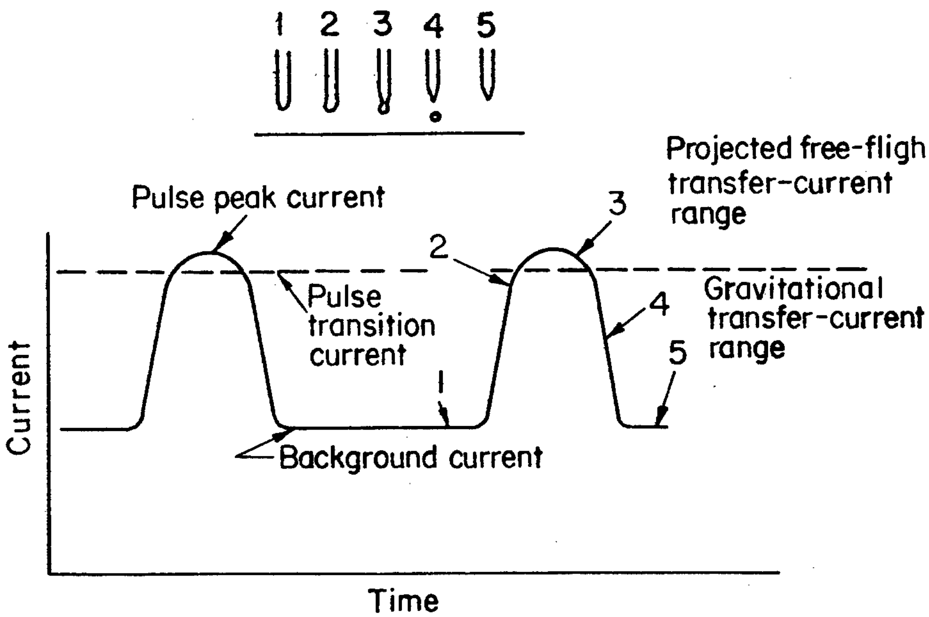


FIGURE 46. ILLUSTRATION OF THE OUTPUT CURRENT WAVE FORM OF THE PULSED-CURRENT POWER SUPPLY; ALSO SHOWING THE METAL TRANSFER SEQUENCE

remains constant. The electrode feeder is then set at the value that will produce the required current. This is also determined by the type and diameter of the electrode. The arc is then initiated and the proper arc length obtained by rotating the background-voltage handwheel.

b. Wire Feed. Because the pulsed-arc process uses a lower deposition rate than the spray-arc process, electrodes must be fed at lower speeds. A wire-feed mechanism should provide speeds from 50 to 725 ipm. Control systems are available that will keep the preset speed within 2 percent, regardless of the load on the motor. Wire-feed mechanisms are generally of the push type and are equipped to be used with either air- or water-cooled guns.

c. Welding Guns or Electrode Holders. The ability to use larger diameter electrodes influences the design of welding guns for pulsed-arc welding. The light, flexible type used for out-of-position welding will not normally accept these electrodes. In addition, the amperage ratings of these guns are generally determined under conditions in which a short-circuiting arc with carbon dioxide shielding is used. These ratings must be redetermined for hotter open-arc, argon-welding conditions for use with the pulsed-arc process.

Section V. FLUX-CORED ELECTRODE GMA WELDING

131. DEFINITION

Flux-cored, tubular-electrode welding has evolved from gas-shielded, metal-arc welding as a result of research to improve arc action and weld-bead appearance. The flux-core welding wire, or electrode, is a hollow tube filled with a mixture of deoxidizers, fluxing agents, metal powders, and ferro-alloys. In one version of the process, the flux core provides all of the shielding gas, slag-forming materials, deoxidizing agents, and alloy additions required. In another version, the arc is shielded with CO_2 in addition to the shielding provided by the flux-cored wire. The composition of the fill will differ somewhat for these two versions; however, the principles of operation for either process are the same as those for gas-shielded, metal-arc welding using spray arc.

132. IMPORTANCE AND USES

a. For applications where bead appearance is most important and where no machining of the weld is desired, the flux-core process is ideal. Carbon dioxide shielding can be combined with rutile-type, flux-cored wires to deposit weld metal with low hydrogen content. The flux-cored wire offers the advantages of increased tolerance for scale and dirty plate. There is also less weld spatter than with solid-wire processes.

b. Weld-metal deposition rates with the flux-cored process is more than twice that of the shielded metal-arc process and is higher than that obtained using the submerged-arc process at equal welding currents. In cases where wire extensions of more than 1 inch can be used, even faster speeds can be obtained without increasing amperage.

c. Because the arc is visible, the weldor may more easily follow the joint and place the weld in the correct position. This reduces weld defects, such as lack of penetration often encountered in submerged-arc welding due to seam-tracking difficulties.

d. By virtue of a deeply penetrating arc and high-deposition rates, the flux-core process offers great economies. It is possible to alter joint designs and greatly reduce the amount of weld metal required. When compared to shielded metal-arc welding, up to 70 percent reduction in labor and 10 percent reduction in material costs may be realized.

e. Flux-cored wire, with CO_2 shielding gas, allows welding of materials of higher strength and alloy content than with solid wire and CO_2 shielding alone. This is because the flux-cored electrode provides a very simple means of adding alloys to the weld deposits.

f. The flux-core process is rapidly being extended from surfacing to fabrication applications. Some of the advantages the non-gas-shielded flux-core process offers are:

(1) High deposition rate

(2) Maximum portability

(3) Visible arc.

g. Tubular electrodes without auxiliary gas shielding are used extensively in hard-surfacing applications. The non-gas-shielded flux-cored process is used both manually and automatically to deposit hard or wear-resistant cladding of tungsten carbide, austenitic manganese, and a wide variety of iron-base surfacing alloys. The process is most widely used, however, in automatic welding, where full advantage can be taken of the high deposition rates that can be obtained using the tubular wires. Deposition rates of 20 to 25 lb of weld metal per hour are quite common. In cases where very high welding currents can be used, deposition rates in excess of 40 lb/hr have been obtained.

133. THEORY.

a. The unsteady arc and spatter associated with CO_2 gas-shielded, solid-filler-wire welding can be altered by using a flux-cored electrode. As the electrode melts in the arc region, the flux serves to improve arc action, metal transfer, weld-metal properties and weld appearance. The addition of an auxiliary CO_2 gas shield produces a deeply penetrating arc and usually better weld quality than the open arc.

b. Weld metal deposited by the open-arc process is generally slightly stronger and a little less ductile than if a CO_2 shielding gas is used; however, weld-metal porosity tends to be lower when auxiliary shielding is used. Impact properties of weld metal deposited from the same flux-cored electrode with and without CO_2 shielding are compared in Figure 47.

c. It appears that, because of these property differences, use of the open-arc should be restricted to those applications where E6012, E6013, E6020, E7014, and E7024 electrodes have performed satisfactorily. The use of CO_2 shielding is recommended where weld-metal properties similar to those available with E-XX16 or E-XX18 electrodes is desired.

d. Most low-alloy or mild-steel electrodes of the flux-cored type are more sensitive to changes in welding conditions than are SMA electrodes. This sensitivity is termed "voltage tolerance" and is most pronounced in low-flux-content mild-steel wires for open-arc welding. The sensitivity can be decreased by the use of a shielding gas, or by increasing the slag-forming components of the core material. Voltage tolerance will vary from grade to grade of wire and also from manufacturer to manufacturer. Because of this voltage sensitivity, best welding results with flux-cored wires are obtained with a constant-potential power source and a constant-speed electrode feeder.

134. EQUIPMENT AND CONTROLS

a. The equipment and controls used for the flux-core process are similar to, and sometimes the same as, those used in gas-shielded, metal-arc welding. Submerged-arc welding equipment may also be used.

b. The most desirable unit consists of a constant-speed wire-drive system. The welding torch, or gun, may be cooled by air, gas, or water. Water-cooled guns are usually used for automatic applications. The welding generator should be a constant-potential d-c unit. It should have a 100 percent duty cycle and a welding current range between 300 and 600 amps. Where high welding-current densities are required, drooping volt-ampere d-c power supplies may be used.

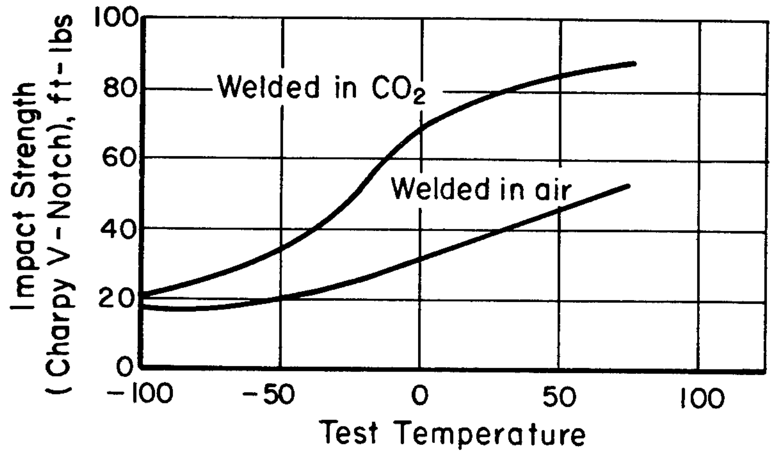


FIGURE 47. IMPACT PROPERTIES OF WELD METAL DEPOSITED WITH AND WITHOUT EXTERNAL GAS SHIELDING

135. ELECTRODES

a. General.

(1) Various designs of flux-cored electrodes have been devised, including tubular shapes or tubular involutes. Figure 48 shows several types of wires in cross section. Present-day cored wires are very hard to distinguish from solid, cold-drawn wire. The closure seam appears only as a fine line, and the density is nearly the same.

(2) Fabrication of mild- and low-alloy steels with flux-cored electrodes is still very much in the developmental stages. Thus, knowledge of electrodes and their capabilities and applications is still quite limited. Some of the grades of flux-cored electrodes presently available for specific material applications are discussed briefly in the following paragraphs.

b. Mild Steel. Flux-cored electrodes not requiring a CO_2 shield can be used for most mild-steel applications. These offer advantages in windy, outside construction areas. However, they are voltage sensitive produce porosity if the arc voltage is too high, and produce large amounts of smoke and fumes.

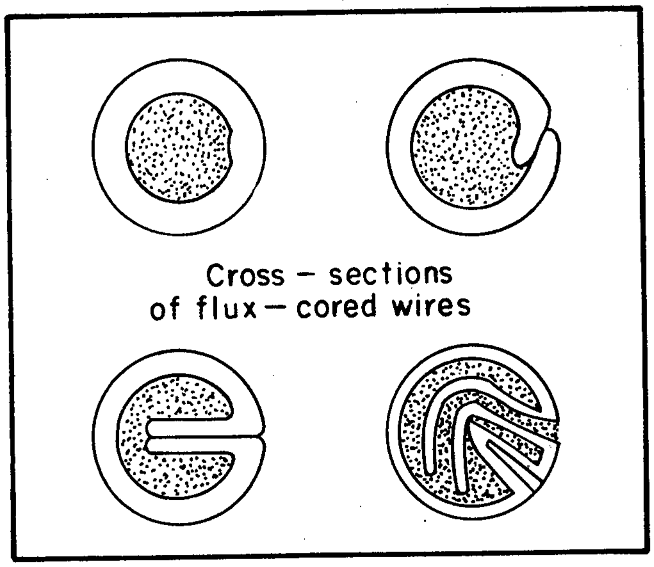


FIGURE 48. CROSS SECTIONS OF FLUX-CORED WIRES

c. Low-Alloy, High-Strength Steels. Electrodes are available that add small quantities of nickel to the weld deposit. This provides the low-temperature notch toughness demanded in subzero climates for mining, road-building, earth-moving, and railway equipment and for bridges and overpasses. Flux-cored wires are also designed for low-alloy, high-strength steel, chrome-molybdenum, and low-nickel steels.

d. Stainless Steel. A number of flux-cored, stainless steel electrodes are available. These electrodes have operating characteristics equal to or better than those of solid stainless steel wires. Composition control with flux-cored electrodes is not as rigid as with solid wires and, therefore, flux-cored electrodes are not recommended for critical applications.

e. Hard Surfacing. Hard-surfacing electrodes were among the earliest developments in the flux-core process. These are available in many compositions of varying hardness and wear resistance. They provide substantial cost savings over coated electrodes.

f. Cast Iron. It is relatively easy to produce an analysis very close to cast iron with flux-cored electrodes. Electrodes for welding cast iron are being developed, and the process could provide a much needed, semiautomatic process for cast-iron repairs and fabrication.

g. Special Products. Flux-cored electrodes are available for use with CO_2 shielding gas, which permits multipass welding without the necessity of slag cleaning between passes. This is called a "low-flux burden type". Arc action and bead appearance with this type of electrode are not as good as they are with the regular flux-cored wire. In multipass joints, these electrodes are used to deposit the root and fill passes. Standard flux-cored electrodes are used for the finish passes.

Section VI. ELECTROGAS WELDING

136. DEFINITION

a. Electrogas welding is a fully automatic process used for butt, corner, and tee joints in the vertical position. The process provides the capability of single-pass welding of heavy sections ranging from 1/2 to over 2 inches in thickness.

b. The electrogas welding operation is usually performed in a rectangular pocket or cavity. This pocket is formed by water-cooled copper shoes that span the gap between the pieces being welded. A curved-wire guide feeds flux-cored wire into this pocket and an electric arc, established between this electrode and the weld puddle, is maintained continuously. A gas suitable for protecting the arc and weld metal is continuously fed into the pocket.

137. IMPORTANCE AND USES

a. Electrogas welding is especially suited for automatic welding of vertical joints in storage tanks, ships, structural beams, etc. The process may be used successfully with carbon steel, low-alloy steel, high-tensile, medium-alloy steel, air-hardening steel, and chromium-nickel stainless steels. In welding alloy steels, there is no need for preheat. Carbon steels may be welded at 32°F without preheating if there is no frost or condensation present. With this process, the full cross section of weld metal may be deposited with a controlled profile. The resulting solidification and shrinkage pattern eliminates warpage and distortion.

b. Presently, the practical limits on plate thickness are between 3/8 inch and 3 inches. Multipass techniques are usually used for the thicker sections. The process has been used most widely in the field erection of various types of pressure vessels and liquid-storage tanks.

138. THEORY.

a. Electrogas welding is essentially a combination of flux-cored, gas-metal-arc welding, and electroslag welding. The weld metal is cleansed by deoxidizers and slagging material from the electrode core. Electrogas welding may also be done using solid wires. Preheating of the workpieces is accomplished by the ionized shielding gas. Single-pass welds can be made on a plate up to 3 inches thick. In theory, the grains of a single-pass weld in carbon steel can be readily refined with a normalizing heat treatment. But practically, the large tanks and vessels usually involved cannot be heat treated.

b. The spacing between the surfaces to be joined is not critical and may vary from 1/2 to 7/8 inch or more. The spacing must be wide enough to permit the wire guide to oscillate without arcing to the sides of the joint. To conserve both weld metal and welding time, the joint spacing should be maintained as narrow as possible. Once established, this spacing remains constant, regardless of the joint thickness. For corner and tee joints, specially shaped shoes are needed to obtain the desired weld puddle.

c. Weld metal may be deposited at rates up to 30 lb/hr with the electrogas process. This rate is a direct function of welding current and may be varied from 20 to 30 lb/hr over a range of 500 to 700 amps using 1/8-inch-diameter filler wire. The electrodes used are the same as those used in flux-cored GMA welding.

d. In single-pass welding, a single flux-cored electrode is used with an auxiliary shielding gas. The composition of the gas is determined by the type of material being welded. The wire is fed through a wire guide or contact tube into the arc. Molten metal is transferred across the arc into the molten pool by spray transfer, using direct-current reverse polarity. The single, large weld puddle is held in the gap between the two plates by the water-cooled copper shoes. As welding progresses, the welding shoes and electrode-feed mechanism move up, maintaining the preset arc length or wire stickout.

e. The flux core of the filler wire promotes good fusion through its cleansing action on the molten metal. The slag which is formed flows toward the copper shoes and forms a protective coating between the faces of the weld and the copper shoes. The principles of single-pass electrogas welding are illustrated in Figure 49.

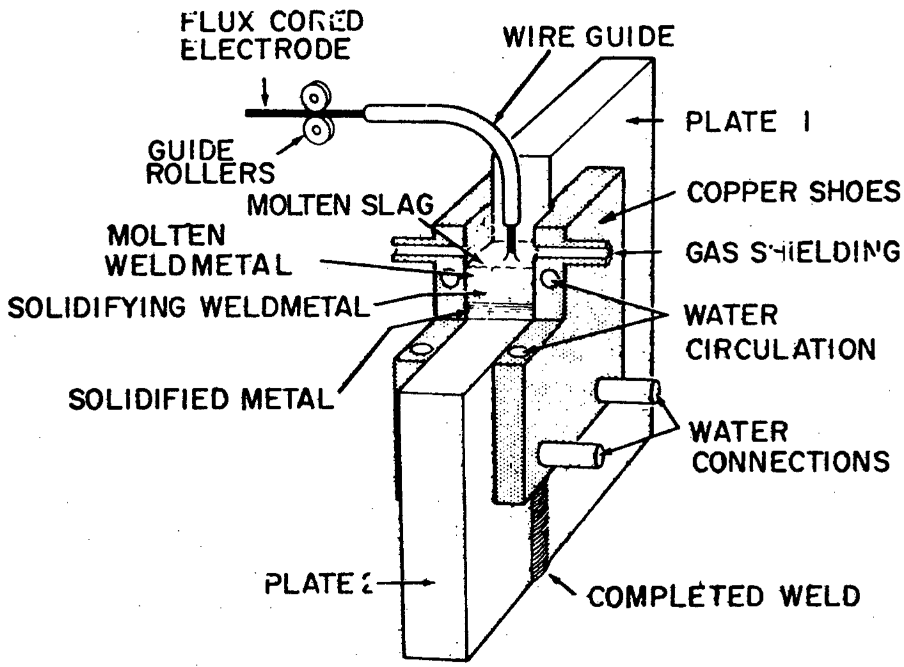


FIGURE 49. SCHEMATIC DRAWING OF ELECTROGAS WELDING PROCESS

f. A multipass technique is generally used for the thicker sections where heat treatment of the weldment is not practical. This forms zones of grain refinement from the heat of subsequent passes and also limits welding heat input.

g. Multipass welding is similar with the exception of shoe and joint designs. Single- and double-vee joints are used, and shoes must be designed to insure that the desired amount of fill is obtained in each pass. The number of shoes required will depend on the number of passes to be made in the weldment. Figure 50 shows a shoe design that could be used to make the first of four passes in 2-inch-thick plate, using a single-vee joint.

139. EQUIPMENT AND CONTROLS

a. Electrogas welding is performed with automatic equipment and controls, which may be adjusted by the operator during welding. The equipment may be designed for light or heavy duty, and it may operate on tracks or hand from a cable or chain. But, essentially, the components are the same.

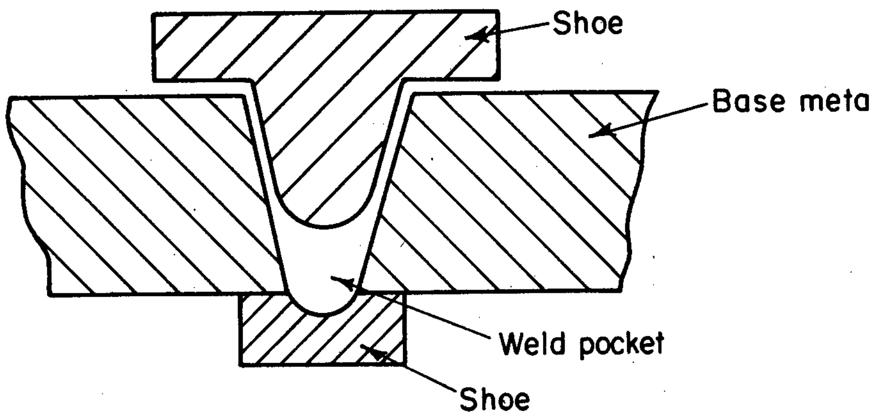


FIGURE 50. SHOE DESIGN FOR FIRST PASS OF A MULTIPASS WELD USING A SINGLE-VEE JOINT

b. The major component is a welding carriage. This carriage contains all mechanical and electrical controls, elevating, traverse, and wire-feed mechanisms. The arms for holding the shoes and an arm to support the filler-wire reel are attached to it. This entire carriage assembly moves upward as welding progresses.

c. To allow electrode oscillation and uniform distribution of heat and weld metal, a horizontal traverse mechanism is usually provided. The oscillation may be automatically interrupted at the end of each stroke. This pause compensates for the cooling effect of the shoes. The oscillation controls the cross-sectional profile of the weld nugget, and the pause after each stroke allows for the formation of weld reinforcement without undercut. This equipment may be used with standard, constant-potential, direct-current welding power sources of adequate capacity.

d. Lightweight, portable equipment is also available which is attached to the work by magnetic or vacuum-cup devices. Because the equipment does not provide for electrode oscillation, it deposits weld metal of fixed profile. Therefore, it is not used with sections over 1-1/4 inch thick.

e. In field work, the equipment is generally protected by an all-weather shelter. This provides protection against the elements and also protects the gas shielding from outside air currents.

140. SHIELDING GAS

The type of shielding gas used for electrogas welding depends upon the application. Argon-CO_2 gas mixtures or pure CO_2 are most commonly used. The gas enters the pocket through the copper shoes above the arc.

141. QUALITY ASSURANCE

a. Control of variables in automatic vertical welding with the electrogas process is not critical; however, the operator must be able to recognize problems as they arise. The operator should be familiar with possible defects and with techniques of inspection that are practical for an operator.

b. Weld defects that may occur include porosity, cold shuts, undercut (or lack of complete fusion), centerline weld bead cracks, and rough surfaces. Porosity may be caused by excessive wind, hose leaks, moisture in the wire or on the plate, insufficient flux, contaminated wire or gas, and air in fusion at weld starts.

c. At starting locations, cold shuts and folds are caused by low heat. In other parts of the weld, they may be caused by short power losses or large surges in travel speed. Preheating may be helpful in eliminating the condition at starts, but all restarts must be carefully inspected.

d. Improper welding conditions, such as low heat input, excessive travel speed, improper wire positioning, or an unusually cold plate, may result in lack of fusion. The operator can usually spot this defect during welding and after solidification.

e. Centerbead cracking may be caused by weld-bead configuration, by crater cracks at the weld termination, or by improper joint design. Pear-shaped deposits and deep flat-sided deposits should be avoided. The use of weld tabs at the start and end of the weld can eliminate crater-crack problems.

f. The weld metal surface appearance is generally of lesser importance, but should be considered. A rough surface may be caused by overheating the copper shoe, by operating the arc too close to the shoe, or by improper flux composition.

CHAPTER 7

GRANULAR FLUX PROCESSES

Section I. SUBMERGED-ARC WELDING

142. DEFINITION

a. Submerged-arc welding is a process wherein fusion is obtained by heating with an electric arc(s) between a bare metal electrode(s) and the work. The welding zone is shielded by a blanket of granular, fusible material on the work. Pressure is not used. Filler metal is obtained from the wire electrode. A supplementary cold filler wire may also be fed into the arc region.

b. The arc, the end of the electrode wire, and the weld puddle are buried under the layer of granular flux. This flux protects the arc area from the atmosphere, adds alloying elements to the weld metal, stabilizes the arc, and controls the weld-bead shape.

143. IMPORTANCE AND USES

a. Submerged-arc welding is used extensively by such industries as the automotive, aviation, shipbuilding, machinery, structural, electrical, ordnance, piping, pressure-vessel and boiler, railroad, and earth-moving industries. The process has been used successfully to make weldments up to 12 inches thick.

b. Both semiautomatic and automatic submerged-arc welding equipment are available. The equipment to be used is usually determined by the type of work to be done. The choice depends on available equipment, economic factors, and process requirements. Semiautomatic equipment is usually preferred for repair welding. It is also used when the geometry of the parts makes automatic welding difficult.

c. In submerged-arc welding, the flux acts as an insulator to keep the welding heat concentrated in a relatively small area. This accounts, in part, for the deep penetration and high weld-metal deposition rates characteristic of the process. High deposition rates are also due to the high welding currents that can be used. The high-current arc is more effectively controlled by the flux than by the gaseous shield of other processes. This high deposition rate results in faster welding speeds than are possible with the gas metal-arc, gas tungsten-arc, or shielded

metal-arc processes. The combination of deep penetration and high welding speed makes submerged-arc welding of thick plates economical.

d. Submerged-arc welding also has certain limitations. For all practical purposes, it is limited to the flat or horizontal position. Because of its deep penetration, it is usually not used to weld material thinner than 1/2 inch, although it is being used for high-speed welding of thin materials in some applications. The deep penetration also makes it necessary to back up single-pass welds or root passes in multipass welds with a steel, copper, or flux backup to prevent burnthrough. Tracking the joint is difficult, because the arc and electrode end are buried under the flux and cannot be seen by the operator.

e. Submerged-arc welding is used primarily for making butt, fillet, and plug welds. Quality of the finished product depends on the cleanliness, fitup, and alignment of the weld joint prior to welding.

144. THEORY

a. Submerged-arc welding takes place beneath the flux covering without sparks, spatter, smoke, or flash. The electrode and weld pool are completely covered at all times during the operation so that there is no visible evidence of the passage of current between the electrode and the workpiece.

b. It is the flux that makes possible the special operating conditions that distinguish the submerged-arc process. When cold, the flux is a nonconductor of electricity. An initial conductive path for starting the arc is therefore needed. In the molten state, the flux becomes highly conductive.

c. The submerged-arc welding process is illustrated in Figure 51. It is usually started by striking an arc beneath the flux on the workpiece. It may also be started by the use of a high-frequency current to create an ionized path. In either case, the heat produced by the current causes the surrounding flux to become molten. This forms a conductive pad, which is kept molten by the continued flow of welding current. Only the buried portion of the flux is melted. The visible portion remains unchanged in both appearance and properties and may be reused.

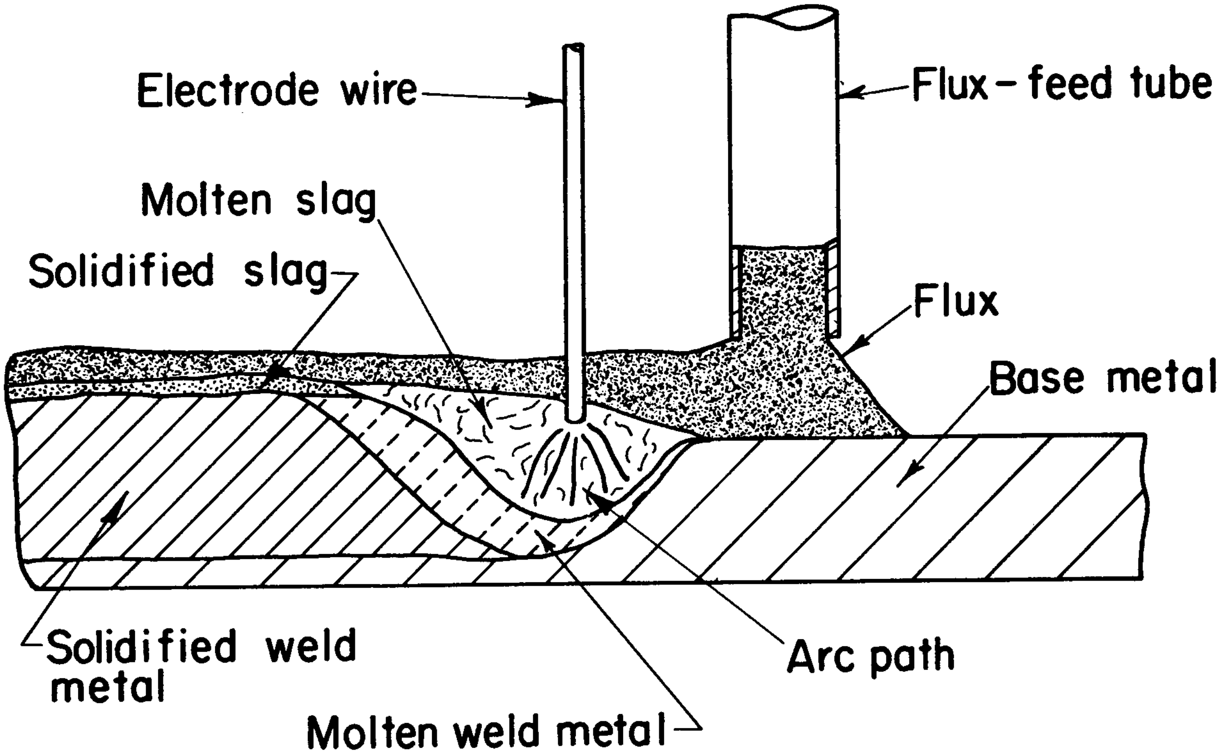


FIGURE 51. DIAGRAM ILLUSTRATING SUBMERGED-ARC WELDING

d. The molten flux allows unusually high currents and, as a result, very intense heat. This intense heat is concentrated in a small welding zone because of the insulating qualities of the flux. This makes possible the high welding speeds and deep penetration, which, in turn, allow use of a relatively small welding groove and less filler metal.

e. Starting the arc, as indicated above, is more difficult than in GMA welding because the flux can prevent contact of the electrode with the work. The methods most frequently used to accomplish this are:

(1) Fuse-ball start. A small, tightly rolled ball of steel wool is placed between the electrode and the work. The electrode is lowered until the ball is compressed slightly. Flux is then applied and the welding current is turned on, burning the ball away.

(2) Pointed wire. The end of the electrode is trimmed to a point with bolt cutters. The electrode is lowered until it just touches the work. After flux is applied, the current is turned on.

(3) Scratch start. The electrode is lowered until it touches the work and flux is applied. Travel of the welding torch along the joint is started and the current is then turned on.

(4) Retract start. This method is used with control systems that have provision for retract starting. The electrode is lowered until it touches the work, and then flux is applied. When the current is turned on, the electrode is retracted, thus starting the arc.

(5) High-frequency start. This type of starting requires special high-frequency starting equipment attached to the welding circuit. Flux is applied to the joint. When the current is turned on, the electrode moves toward the work. When the end of the electrode is about 1/16 inch away from the work, a high-frequency spark will jump from the electrode to the work. The welding arc then will be established along this spark path.

145. WELDING CURRENT

a. Alternating or Direct Current. Direct current is preferred where (1) fast, accurate arc striking is essential, (2) close arc control is needed, and (3) difficult contours are to be followed at maximum speeds. Using direct-current, reverse polarity gives the best control of bead shape, but higher deposition rates are possible with straight polarity. Direct-current, reverse polarity provides maximum penetration and direct-current, straight polarity minimum penetration. Alternating current provides penetration somewhere between the two. It also minimizes arc blow, which is important at higher welding currents. Alternating current is usually preferred for multiple-wire, multiple-power welding.

b. Multiple Arcs. The use of multiple arcs in submerged-arc welding increases melt-off rates and directs arc blow so as to increase welding speed. This method also lowers the freezing rate and reduces weld-metal porosity. Submerged-arc welding is highly adaptable to both multiple-arc, single-power source and multiple-arc, multiple-power-source applications, as described in Chapter 3, Section IV. To obtain uniformly high-quality welds with these techniques requires the use of

good-quality base material, free from rust, scale, moisture, and other surface impurities.

c. Figure 52 shows the deposition rates that may be expected from various submerged-arc welding techniques. Data are shown for manual shielded-metal-arc welding for comparison.

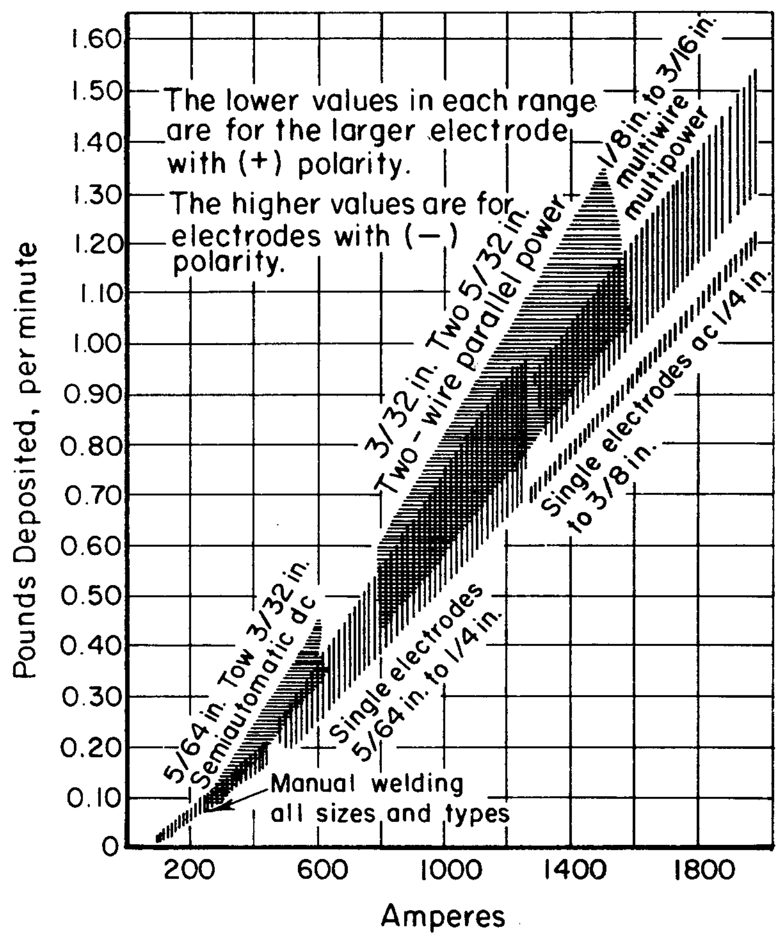


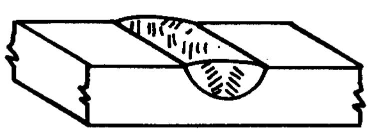
FIGURE 52. APPROXIMATE DEPOSITION RATE OF SUBMERGED-ARC PROCESS ON MILD STEEL

146. POSITION AND ALIGNMENT

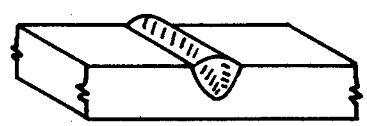
a. Weld Setup. For all submerged-arc-welding applications, the joint must be assembled and held securely to limit distortion caused by

...at. This may be done by tacking, clamping, jigging, or a combination of these. With very large, heavy assemblies, tack welding is sufficient, as the weight of the assembly will prevent distortion. Lighter assemblies require clamping to prevent distortion during welding.

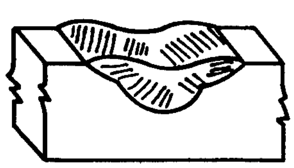
b. Inclination of the Work. While most submerged-arc welding is done in the flat position, it is sometimes necessary to weld with the work slightly inclined. Figure 53 illustrates welds made on flat plates, on slanted plates welding uphill and downhill, and on plates with a lateral slope. In uphill welding, the force of gravity causes the weld puddle to flow back and lag behind the welding wire. Metal flows to the middle from the edges of the weld. The center buildup and penetration increase as the angle of inclination increases. At the same time, the width of the weld decreases. With downhill welding, the weld puddle flows toward the welding wire and preheats the base metal. An irregularly shaped fusion zone called a "secondary wash" results. As the angle of inclination increases the middle surface of the weld is depressed, penetration decreases, and the width of the weld increases. Lateral inclination produces a predictable effect as shown in Figure 53(d). The limit for lateral slope is approximately 3 degrees, or 5/8 in./ft. This will vary somewhat with the size of the weld puddle.



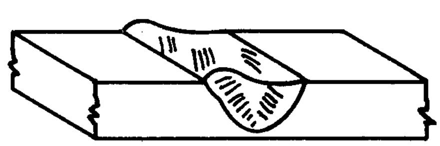
a. Level Weld on 1/2-In. Plate



b. Uphill (1 1/2 In./Ft.) Weld on 1/2-In. Plate



c. Downhill (1 1/2 In./Ft.) Weld on 1/2-In. Plate



d. Lateral Slope (5/8 In./Ft.) Weld on 1/2-In. Plate

FIGURE 53. EFFECT OF WORK INCLINATION ON BEAD SHAPE IN SUBMERGED-ARC WELDING

c. Positioning the Welding Wire.

(1) There are three factors to be considered in determining the proper position of the welding wire:

(a) The alignment of the welding wire in relation to the joint

(b) The angle of tilt in the lateral direction

(c) The direction in which the welding wire points--forward or backward.

Proper alignment of the wire and workpiece for a butt joint is shown in Figure 54. For work 1/2 inch and thicker, good stability can be obtained with a vertical welding wire. For thin sections, however, the wire should point backward, 25 to 45 degrees from the vertical, for voltage stability.

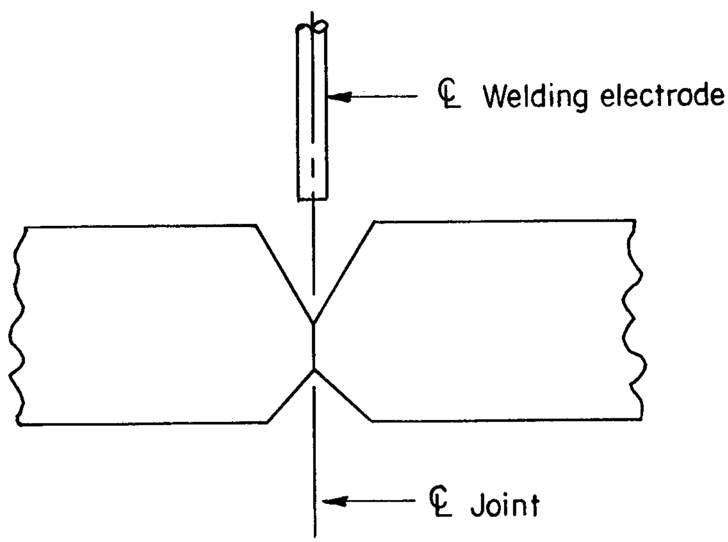


FIGURE 54. PROPER ELECTRODE ALIGNMENT FOR SUBMERGED-ARC WELDING OF BUTT JOINTS IN THE FLAT OR HORIZONTAL POSITIONS

(2) Figure 55 shows proper wire alignment for horizontal fillet welding. The center line of the wire should be off the joint center line a distance equal to about 1/2 to 1/4 of the wire diameter. The great distance is used for larger size fillet welds. The wire is tilted 20 to 45 degrees from the vertical. The exact angle of tilt is determined by: (1) clearance for the nozzle or jaw assembly, and (2) the relative thickness of the joint members. Where there is a possibility of burning through one of the members, the wire must be directed toward the thicker member.

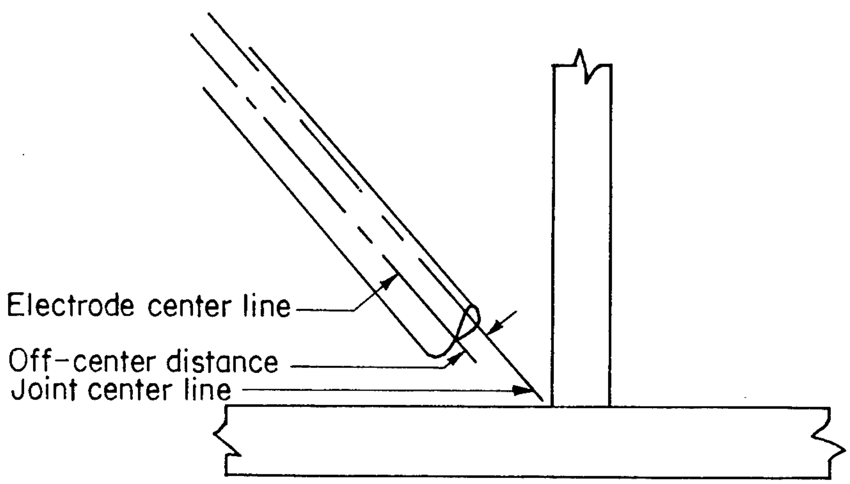


FIGURE 55. PROPER ALIGNMENT OF THE WELDING ELECTRODE FOR SUBMERGED-ARC WELDING OF A HORIZONTAL FILLET

147. EQUIPMENT AND CONTROLS

a. General. The equipment required for submerged-arc welding includes a welding nozzle, wire-drive mechanism, power supply, control equipment, and flux-feeding equipment. Equipment for picking up the loose flux after the weld is completed is useful but not necessary.

b. Welding Torch. The welding torch or gun consists of a current pickup and a wire guide. These can be combined in a copper tube or spring-loaded copper jaws. A gas metal-arc welding torch can be used for submerged-arc welding if the gas nozzle is removed. For automatic welding, the torch is mounted on the wire-drive mechanism. For semi-automatic welding, the torch is held and manipulated by the welder.

c. Wire-Drive Mechanism. The wire-drive mechanism is comprised of an electric motor, or motors, which power a set of wire-drive rolls. A constant arc length is maintained by one of two types of control systems. One type controls the arc length by varying the speed of the wire-drive motor. This is called arc-voltage control. This system is good for close control of bead shape. This control also has the ability of "retract starting". The second type of control is known as a current control. The wire is fed at a constant rate as in gas-metal-arc welding. If the arc becomes too long or too short, the current is automatically varied by the power supply to bring the arc back to the desired length. This system is used when high welding speeds are required, or when quick changes in contour occur.

d. Power Supply. The power supply used for submerged-arc welding may be d-c constant current, d-c constant voltage, or a-c. Direct-current power supplies may be either motor generators or rectifiers. Transformers are used for a-c power supplies. The power supply and the wire-drive mechanism must be designed to operate together so that effective control of the arc length can be maintained. Constant-current types of power sources are used with arc-voltage controls. If current control is used to regulate the arc length, a constant-voltage power supply must be used. Submerged-arc welding generally is done at higher currents (500 to 1000 amperes) than other types of arc welding, so the power supply must have a high current rating at high duty cycles.

e. Flux Distribution. The granular flux is fed from a hopper to the arc area through a pipe or flexible hose. The flux is discharged at a point immediately ahead of the welding arc. For semiautomatic welding, a small hopper is attached to the welding gun held in the operator's hand. After the weld is completed, loose flux may be swept up and reused. More

effective flux pickup can be obtained by using a vacuum pickup device. An industrial vacuum cleaner works very well. Where long welds are to be made, the vacuum pickup can be mounted a short distance behind the welding nozzle so that the flux will be picked up automatically as the weld progresses. Figure 56 shows typical submerged-arc welding equipment set up for automatic welding in the flat or horizontal position.

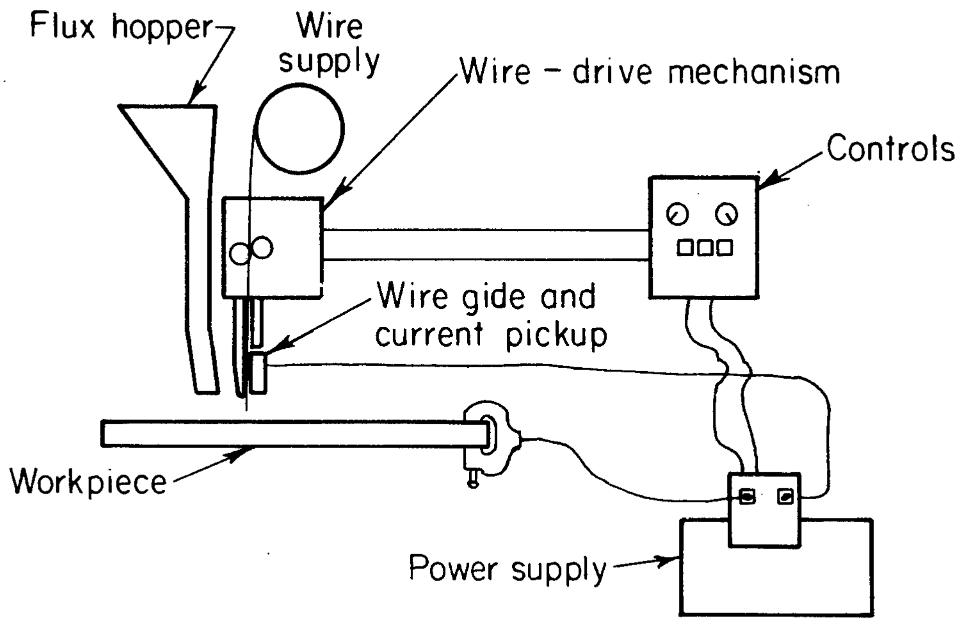


FIGURE 56. AUTOMATIC SUBMERGED-ARC WELDING EQUIPMENT AND CONTROLS FOR AUTOMATIC WELDING IN THE FLAT POSITION

148. ELECTRODES AND FLUXES

a. General

(1) The choice of either filler wire or flux will also depend on the amount of dilution of the weld metal by the melted base metal. Dilution is of more concern in submerged-arc welding than in other arc processes because of the greater penetration that is obtained. Dilution can vary from 10 percent to 75 percent with varying joint designs. The selection of a proper flux and electrode should be based on the particular joint to be welded.

(2) The size of filler wire used depends on the range of welding current to be used. Welding flux is available in different particle sizes. The size that is used also depends on the current and the composition of the flux. The manufacturer's recommendations should be followed when the flux particle size is being selected.

b. Electrodes

(1) The electrodes used with submerged-arc welding are generally bare rods or wires. They have clean, bright surfaces which facilitate introduction of relatively high currents. Choice of electrode is based on the three methods by which alloying elements are introduced into submerged-arc welds:

(a) The use of special-alloy steel electrodes

(b) The use of fluxes containing the alloy elements in conjunction with mild-steel electrodes

(c) The use of a composite electrode as a sheath enclosing the alloy elements.

(2) The compositions of electrodes include: low-carbon steel, low-carbon alloy steel, special-alloy steels, high-carbon steels, stainless steels of various grades, nonferrous alloys, special alloys for producing hard-surfacing, and corrosion-resistant deposits.

(3) Table XXI shows the generally accepted current ranges for commonly used submerged-arc welding wire diameters. The current contact jaws must be in good condition and located close to the work. Otherwise, poor current transfer will result and the wire will heat irregularly above the welding zone.

c. Fluxes

(1) Submerged-arc welding fluxes are granulated, fusible, mineral materials. They are largely free of substances capable of evolving large amounts of gases during welding. Silica is a major ingredient of many fluxes, and there is no

health hazard in its normal use. The particular flux used depends on welding procedures, type of joint, and base-metal composition. Fluxes come in a range of particle sizes and are made according to several chemical specifications. The flux may include alloying elements.

TABLE XXI. CURRENT RANGES FOR VARIOUS WIRE SIZES USED IN SUBMERGED-ARC WELDING

Wire Diameter, in.	Current Range, amp
3/32	120 - 700
1/8	220 - 1100
5/32	340 - 1200
3/16	400 - 1300
1/4	600 - 1600
5/16	1000 - 2500
3/8	1500 - 4000
1/2	2000 - 4800

(2) The use of alloy fluxes has helped solve the problem of obtaining welding wire of satisfactory composition to match weld-metal properties to base-metal properties. Using a commonly available mild-steel electrode, a wide variety of weld-metal compositions is possible by varying the type and amount of alloy in the flux. In order to maintain a consistent weld-metal composition, it is necessary to keep a fixed ratio between the amount of flux melted and electrode melted. This ratio is controlled by the welding procedures.

(3) Alloy fluxes are widely used for joining stainless steel to a base metal of lesser alloy content. These fluxes contain either ferro-alloys or elemental metals, they are used with alloy electrodes to add alloying elements not readily available in electrode compositions, to compensate for alloy losses during welding, and to compensate for dilution from the base metal.

149. QUALITY ASSURANCE

a. General. There are six variables in submerged-arc welding that require proper control if consistently good welds are to be obtained. An operator should know how each of these affects the welding action and how to change them to achieve a desired result. These variables are listed in their approximate order of importance and discussed in the following paragraphs:

(1) Welding current

(2) Welding voltage

(3) Welding speed

(4) Wire extension beyond current contact tip

(5) Width and depth of the layer of flux (flux burden)

(6) Mechanical adjustments.

b. Welding Current.

(1) The welding current controls the rate at which the electrode is melted, the depth of fusion, and the amount of base metal fused. If the current is too high, the depth of fusion will be too great and the weld may melt through the backing. The higher heat may also extend the heat-affected zone of the plate excessively.

(2) Welding current may change slowly while long seams are being welded. This is because the shape and electrical characteristics of the circuit change as the weld progresses. Connecting the ground to both ends of the workpiece will allow a more uniform weld. When only one ground connection is used, the direction of welding should be away from the ground connection.

(3) The current-carrying cables should be kept as close together as possible. They should be kept free of coils and should not be hung around metal objects. This is specially true when alternating current is being used.

c. Welding Voltage. Welding voltage is the potential difference between the tip of the welding wire and the surface of the molten weld metal. It varies with the length of the gap between the welding wire and the metal. As the gap increases, welding voltage increases. The voltage determines the shape of the weld zone and reinforcement. Higher voltage produces a wider, flatter, less deeply penetrated weld.

d. Welding Speed. If welding speed is increased while current and voltage remain constant, there is less heat input per unit length of weld, resulting in less weldingwire melted per unit length of weld, and less weld reinforcement. A decrease in welding speed results in exactly opposite effects. In general, if the welding speed is decreased, weld penetration will decrease. In the same manner, if the welding speed is increased penetration will increase.

e. Wire Extension. For best results, the current contact tip should be held close to the work. This becomes more important as the current density increases. Above 80,000 amp/in.^{2} of electrode cross section, heating of the electrode between the point of emergence from the contact tip and the arc takes place because of the resistance of the wire. The amount of heating increases as the extension of the electrode increases. This increases the electrode melting rate and decreases the penetration.

f. Flux Burden

(1) The flux burden (width and depth of the flux layer) affects both the weld appearance and the welding action. A flux layer that is too deep will produce an uneven weld because the gases generated during welding cannot escape. If, on the other hand, the flux layer is too shallow, the welding zone will not be entirely submerged. This will allow flashing and spattering and a weld of poor appearance, with possible porosity. The proper depth of flux can be determined by slowly increasing the depth of flux until the welding action is submerged and flashing no longer occurs.

(2) If the flux layer is too narrow, it will interfere with the lateral flow of weld metal. The result is a narrow reinforcement and a weld that is steep sided. Normally, the flux layer should be about three times the width of the fused portion. For large welds, a wider flux layer may be needed.

(3) Flux removal is another matter of importance. The unfused flux can be removed a short distance behind the welding zone where the fused flux has solidified. Under some conditions, however, it may be best to leave the flux intact until the heat has become distributed throughout the section. Care should be taken to ensure that no foreign material is picked up with the reclaimed flux. If the recovered flux contains pieces of fused slag, it should be passed through a screen with openings no larger than 1/8 inch. If the flux becomes wet, it should be dried thoroughly before use to prevent weld porosity.

g. Mechanical Adjustments

(1) The weld joint should be clean, dry, and free of foreign matter. The cleaning techniques used with gas metal-arc or shielded metal-arc welding should be used to clean the joint area prior to submerged-arc welding. The pieces to be welded should be aligned and tack welded or clamped. Special steps should be taken to prevent burnthrough when a single-pass or the root pass in multipass welds are being made. Welding-wire position and alignment, joint alignment, jigging and clamping, and the precautions to be taken with various types of welds were discussed in Paragraph 143 of this section.

(2) After the weld is completed, all loose flux should be removed from the joint and the slag covering the bead should be chipped away. When multipass welds are being made, it is very important that all slag is removed from the weld surface before the next pass is deposited. Slag remaining on the weld may become entrapped by the next pass. Slag can usually be easily removed with a steel chipping hammer. Grinding may be required to remove slag along the edges of the bead.

Section II. STRIP-ELECTRODE SUBMERGED-ARC WELDING

150. DEFINITION

a. Strip-electrode welding is a variation of submerged-arc welding that uses a thin, wide strip as an electrode rather than the conventional

wire. This strip is fed vertically into the submerged-arc and advanced broadside across the work. It deposits a wide bead, with uniform penetration and dilution of the base metal.

151. IMPORTANCE AND USES

a. Submerged-arc strip-electrode welding is used primarily for overlaying low-cost base metals with more costly corrosion-resistant or wear-resistant metals. It has been used to clad heat exchangers, water turbine blades, reactor tanks, and similar objects with overlays of stainless steels, Inconel, Monel, copper-nickel alloys, aluminum, bronze, and copper. For many cladding operations, it may be more economical to apply the overlay by submerged-arc strip electrode than by other cladding methods such as hot-roll bonding and explosive cladding.

b. The strip-electrode process is limited to the flat position because of the very large molten weld puddle associated with it. Most hard-surfacing operations in which the overlay is applied by automatic welding in the flat position can be done faster and cheaper by automatic, strip-electrode welding. Wear-resistant, hard facing is used to improve the wear resistance of parts such as roller, tracks, shovel teeth, buckets, and blade edges of earthmoving and related equipment.

152. THEORY

a. In strip-electrode welding (strip welding) the strip is fed vertically into a submerged arc and advanced broadside across the work. Penetration into the base metal is more uniform than with wire electrodes at about the same average base-metal dilution.

b. Strip welding is done with either a single-strip electrode or with dual strips. When dual strips are used, one acts as the electrode and the other is used as a cold barrier strip between the electrode and the work. The barrier strip increases the rate of metal deposition and decreases base-metal dilution.

c. In strip welding, the arc traverses rapidly back and forth across the width of the strip in random oscillation. This melts the strip in a rapid succession of small increments. The resulting deposit is a thin layer, slightly wider than the original strip. Penetration is uniform across the full width, similar to the deposit of an oscillating-wire electrode. Dilution varies with travel speed, and may range from 10 to 50 percent. Dilution can be controlled within a 10 to 15 percent range in dual-strip welding by using the proper thickness of barrier strip.

d. The chemical composition of the various components determines the composition and microstructure of the overlay. These components are: the electrode strip, the barrier strip, the base metal, and the submerged-arc flux.

e. The electrode shape does not appear to influence melting rate under the submerged 1=1 arc. A strip electrode burns off faster than a wire electrode because of the higher current that can be used with the strip.

153. WELDING WITH A SINGLE STRIP

a. The strip electrode is fed similarly to the wire electrode in regular submerged-arc welding when welding with a single strip. Uncoiled from a reel, it passes between drive rolls and through an automatic welding head. Granular flux is added both in front of and behind the arc. This is done to avoid arc flashing caused by the strip pushing the flux ahead of the arc. A single-strip electrode is capable of depositing up to 60 pounds of weld metal per arc-hour.

b. Strip electrodes are available in different thicknesses and widths, generally 0.020 to 0.030 inch thick and 2 to 4 inches wide. Strips wider than 4 inches are considered impractical, although they may be used.

c. Voltage deviations within a limited range are of little importance in surfacing operations except for differences in flux consumption and alloy pickup. Changes from 26 to 36 volts do not significantly affect bead dimensions. However, arc voltages over 40 volts result in the formation of a large pool of molten slag and converts the process from an arc to an electroslag welding process. This brings an abrupt deterioration of bead shape and soundness. When the arc voltage nears 26 volts, the arc becomes unstable and frequent short circuiting occurs.

d. Welding speed is an important factor in strip welding. Travel speed depends on the thickness of overlay desired, but ranges from 10 to 20 ipm. At a given current, the melting rate decreases slightly as travel speed increases. This is because a higher proportion of the arc heat is used to fuse the flux at higher travel speeds. In addition, dilution increases sharply because of the marked increase in penetration and decrease in bead thickness.

e. Flux is consumed at a rate of 0.3 to 0.4 lb/lb of electrode melted in strip welding. Slag coverage with the process is quite thin at the center

of the bead and somewhat thicker at the edges. This can be affected by flux composition, however, because some fluxes melt faster than others and form thicker slags.

f. The preferred electrode "stick-out" for strip-electrode welding is 1-1/4 to 2 inches. Beyond 2 inches, the electrode begins to overheat from resistance heating. If the contact jaws are closer to the arc than 1 inch, the end of the jaws become clogged. However, there are practically no changes in melting rate, bead dimensions, or penetration for variations in stick-out between 1/2 and 2-1/4 inches.

154. WELDING WITH DUAL STRIPS

a. The barrier strip in dual-strip welding is preplaced in contact with the work and consumed in place, inch by inch. The process requires a suitable strip-welding head with a reel and hold-down devices for the cold strip.

b. Barrier-strip width is closely related to the width of the electrode strip. The electrode strip should overlap by about 1/2 inch on each side. This ensures both the complete melting of the barrier strip at each edge and an adequate region of remelting of the previous bead to secure a smooth tie-in. The barrier strip must be thicker than the electrode strip to control dilution. It is fed from a coil at a speed synchronized with that of the welding head or work surface.

c. Weld puddles up to 2 inches wide have proved workable and reliable at deposition rates of 100 lb/arc-hr with dual-strip welding. The width of puddle that can be tolerated depends on the flatness of the surface and the stability of the fixturing. If the weld puddle is not level, it will flow to the side and eventually leave an uncovered area as the metal contracts. If the work is disturbed by such things as uneven or erratic turning rolls, defects in surface coverage can result. Both these problems mount with the size of the weld puddle.

d. Travel speed in dual-strip welding must be adjusted to match the current and voltage. When travel speed is too fast, the bead forms holes or voids in the surface. When travel speed is too slow, the bead rolls over at the outer edge and forms a needlessly thick deposit. A travel speed of about 12 ipm is recommended for a current of 1200 amperes. This will produce a deposit with 1/4-inch maximum thickness.

e. Straight polarity is preferred for the dual-strip process. Although reverse polarity gives thinner beads with straighter edges, penetration and dilution are higher. With straight polarity, the weld edges are somewhat irregular, and slag removal is slightly more difficult. Straight polarity is preferred because of the lower dilution.

f. An arc voltage range of 29 to 34 volts seems best for dual-strip welding. Below 28 volts, the strip electrode frequently shorts out and sticks to the work. Penetration is reduced with higher voltage, but the risks of poor tie-in to the previous bead and of slag entrapment are increased. There is more spatter with higher voltages.

g. The prime objective in strip welding is to cover the surface rapidly at the desired thickness with minimum dilution. In dual-strip welding, current is the principal factor. The heat input must be considered in relation to the amount of strip metal available to absorb the energy. Dilution will be reduced by using more barrier material at the same current. Dilution can also be reduced by a reduction in current; however, this also reduces the deposition rate and is not as economical.

155. EQUIPMENT AND CONTROLS

a. Since the strip electrode is in series with the workpiece, strip welding is, in principle, performed in the same way as in conventional submerged-arc welding. Therefore, simple welding equipment and controls may be used. Standard submerged-arc equipment, fitted with special electrode spools, drive rolls, and current contacts, can be used with the process. The power source should be capable of delivering high currents (600 to 1500 amperes) for extended periods of time. Either a-c or d-c power can be used; however, d-c power supplies with slightly drooping volt-ampere characteristics are preferred.

Section III. ELECTROSLAG WELDING

156. DEFINITION

Electroslag welding uses a molten slag to melt the filler metal and the surfaces of the metal being welded. This molten slag also acts as a shield by covering the entire cross section of the joint during welding. It is electrically conductive and remains molten because of its resistance to the current flowing between the electrode and the work. Single-pass welding of heavy plates in the vertical position is accomplished by using multiple consumable electrodes. The molten weld metal and flux are contained by copper shoes placed on either side of the space between the plates being welded.

157. IMPORTANCE AND USES

a. The electroslag process is relatively new, and has only recently come into use in the United States. However, the process has been used extensively in Europe for several years. It can be expected to find wider use in this country for vertical welding of longitudinal seams in heavy-wall pressure vessels for the chemical, petroleum, and power industries.

b. Some of the numerous applications for which electroslag welding has been used in Europe include: structural members, pressure parts in nuclear reactors, high-pressure boiler drums, forged crankshafts, press frames, cylinders for hydraulic presses, turbine and alternator shafts, rolling 1 = 1 mill frames and ship hulls. The normal thickness range for electroslag welding is 1 to 20 inches.

c. Materials that have been electroslag welded include mild and low-alloy steels, several high-strength steels, stainless steels, and high nickel-chromium alloys. Gray cast irons and titanium have been welded abroad. However, not all of these materials have been production welded.

158. THEORY

a. Electroslag welding is initiated by striking an electric arc beneath a layer of granular flux, much like submerged-arc welding. However, as soon as the layer of molten slag becomes thick enough, arc action stops. The current passes from the electrode to the workpiece through the conductive slag, and electroslag welding has begun. Fusion results from the heat generated by the resistance to flow of current through the molten slag. Because there is no arc, no spatter or intense flash occurs. The temperature of the slag is about 3500 F. Liquid metal from the filler wire and base metal collect in a pool beneath the slag and slowly solidify to form the weld. The process is illustrated in Figure 57.

b. Electroslag welding is generally done in the vertical position because of the large amount of molten slag and weld metal produced. The gap between the pieces being welded is about 1 to 1-1/4 inch. The edges of the joint can be square cut and need not be beveled. A U-shaped starting tab is used to start the weld in order to build up the proper depth of conductive slag. In the same manner, a dam is required at the end of the seam for the conductive slag to run-off the weld. Both tabs are later removed flush with the ends of the seam.

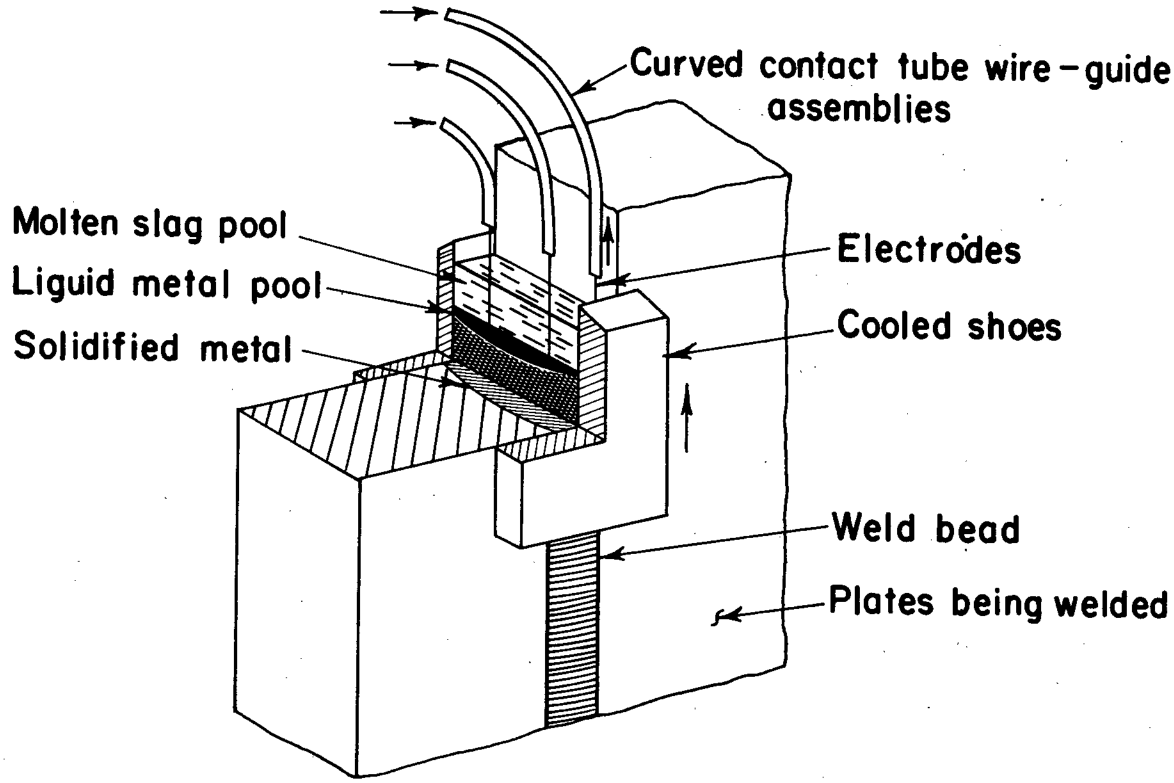


FIGURE 57. SCHEMATIC VIEW OF CONVENTIONAL ELECTROSLAG WELDING PROCESS

c. Welding can be done with one or more electrodes, depending on the material thickness. The electrodes are fed through the contact tubes in the wire-guide assembly. This assembly is oscillated slowly back and forth during welding. This is done to obtain even heat distribution across the joint in order to maintain uniform penetration.

d. The molten metal and slag pool are contained by water-cooled copper shoes that ride along each side of the joint. These shoes also act as a mold to cool and shape the weld surfaces. The weld surface is covered with a thin layer of slag as it solidifies. This layer is easily removed when it is cool. This slag consumption must be compensated for, however, by feeding flux to the slag pool during welding. This can be done either manually or by an automatic dispenser.

e. For each electrode used, electroslag welding deposits 35 to 45 pounds of filler metal per hour. An electrode wire 1/8 inch in diameter is generally used, and electrode metal transfer efficiency is nearly 100 percent. Flux consumption is only about 1/20 of the wire consumption.

f. Electroslag welds are usually distortion free. This is due to the uniform heat distribution throughout welding. The weld-penetration contour is a function of the welding voltage, and slag-pool depth and usually consists of approximately 30 to 40 percent of fused base metal.

159. CONSUMABLE CONTACT TUBES

A variation of electroslag welding uses a consumable contact tube. In this process, the tube that guides the electrode wire is also melted down to act as filler metal. For this process, the chemical composition of materials from which the contact tubes are made must be controlled to achieve the desired weld analysis. The contact tubes are made from metal strips, sheet, or tubes, with a channel provided for passage of the electrode wire. The consumable contact tube is located in the weld groove prior to welding. It has the general contour of the weld joint. The electrode is fed into the molten pool in the same way as conventional electrode wires to furnish additional filler metal. Sliding shoes are not usually used with this process, but a copper backing bar or a permanent steel backing strip is used to contour each side of the weld surface. The contact tube may be insulated with fiber-glass plates to prevent arcing during welding.

160. PLATE-ELECTRODE WELDING

Plate-electrode electroslag welding is another form of electroslag welding. This process uses electrodes in the form of plates rather than wire. A single-plate electrode may be used for light sections (4 to 6 inches thick). The plate is as wide as the work being welded. As many as three plates, side by side, may be used for heavier sections. The dimensions of the plates are determined from the volume of metal needed to fill the joint. Plate-electrode welding is illustrated in Figure 58. This process provides more uniform heating of the slag pool. It is more stable and can be used with higher currents and lower voltages than conventional electroslag welding. With the larger cross-section electrodes, currents as high as 1500 to 2000 amps are used. Because of the more uniform heating of the slag pool, a shallower depth of molten slag is possible.

161. PREPARATION AND ASSEMBLY

A major advantage of electroslag welding is fairly simple weld preparation. Only a straightedge is needed on the groove faces, and this can be produced by thermal cutting, machining, etc. However, it is necessary to have a smooth face on either side of the groove to prevent slag leakage when copper

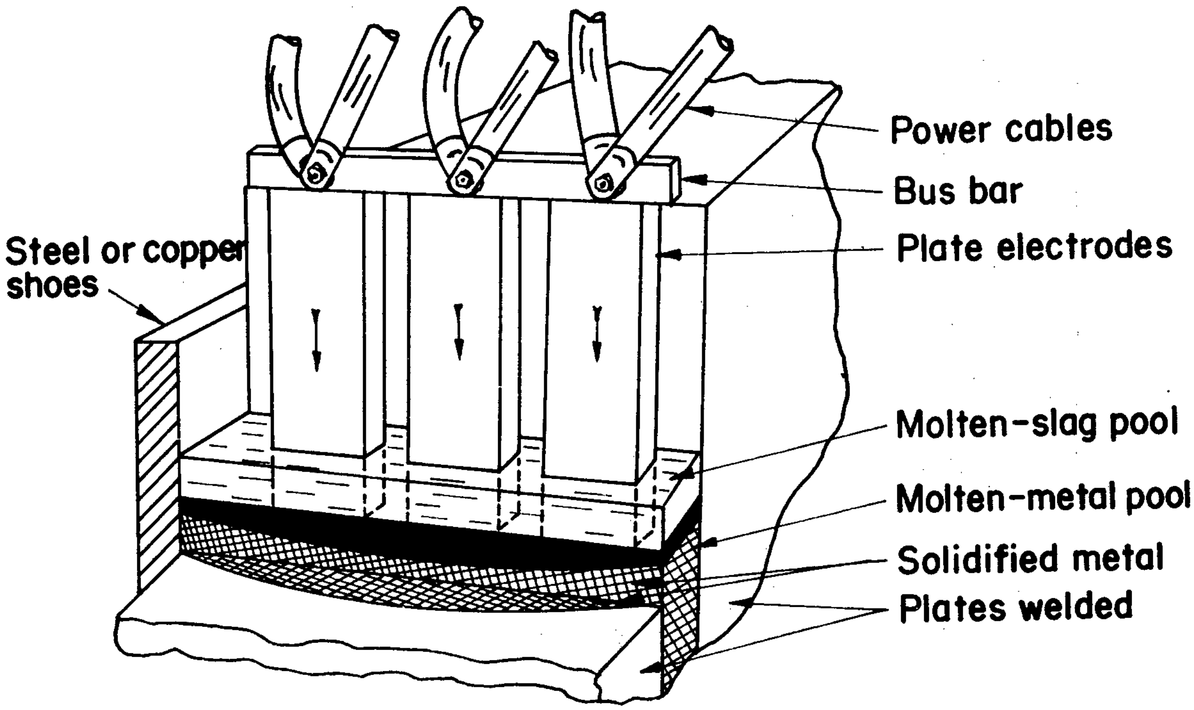


FIGURE 58. SCHEMATIC VIEW OF PLATE-ELECTRODE ELECTRO-SLAG WELDING

shoes are used. The parts may be assembled in several ways, including horseshoe-shaped clamps or simple bars, which are removed as welding progresses. In welding of massive parts, their weight alone provides adequate restraint. For 7- to 8-inch plate, the gap opening at the start end of the weld may be as much as 1-1/2 inch. For 2- to 3-inch plate this may be only 1 inch. Because of shrinkage and contraction of the weld metal previously deposited, the gap opening at the finish end will generally be about 1/4 inch wider than at the start. Butt joints are most commonly used with the process, but corner and tee joints may also be used. Circumferential joints are made on turning rolls, with the welding head kept stationary at the 3-o'clock position.

162. ELECTRODES AND FLUXES

a. In selecting electrode wires for electroslag welding, it should be remembered that as much as 40 percent of the weld cross section consists of base metal because of the deep penetration. In addition, all wires and

base metals should be low in elements that adversely affect notch toughness, such as sulphur, phosphorus, and oxygen. This is necessary because of the large dendritic, as-cast structure of the slow cooling electroslag weld metal. Three types of electrode wires may be used: solid wires, flux cored or composite wires, and braided or twisted wires. The wires should contain much less carbon than the base metal when carbon and low-alloy structural steels are being welded. Usually, additional alloying of the weld metal with manganese, silicon, or other elements is used to give it the strength characteristics of the base metal. For higher carbon and alloy steels, it is usually best to have weld and base metal as similar as possible in composition and mechanical properties.

b. A flux containing manganese and aluminum silicates with small additions of calcium fluoride is used for practically all electroslag welding. This combination offers the best slag conductivity, stability for long welding runs, uniformity of viscosity, speed of starting, and slag removal. This flux permits only small increases in conductivity with rising temperature, which is necessary for stability to prevent arcing on the surface of the pool. The viscosity of this flux is uniform to prevent leakage of a too-fluid slag. If a slag is too viscous, it will build up on the copper shoes and prevent fusion at the plate surface.

163. THERMAL CYCLE

Because there is no arc, heat concentration in the electroslag process is considerably lower than in submerged-arc welding. Thus, electroslag welding has lower heating rates but longer holding times. The heat-affected zone is considerably wider than in conventional arc welding. With multiple electrodes, cooling is even slower.

164. PREWELD AND POSTWELD HEATING

a. Preheating of base metals is usually unnecessary in electroslag welding. Much of the heat generated in the process is carried away into the workpieces. This serves to preheat the base metal.

b. Many electroslag welding applications require no heat treatment after welding. However, where optimum mechanical properties are required, heat treatment is necessary. Stress-relief heat treatment will improve ductility in mild-steel weldments. It will also have a slight effect on base-metal heat-affected-zone properties.

165. EQUIPMENT AND CONTROLS

a. The most common types of electroslag welding machines are one-, two-, or three-electrode machines. The one-electrode machine is used to weld plates up to 5 inches thick, while the two-wire machine can be used for plates up to 10 inches thick. The three-wire machine is used for greater thicknesses. A single machine may be adaptable for one-, two-, or three-wire welding. However, for greater portability, small one- or two-wire machines are preferred where applicable. For thicknesses of material greater than 20 inches, the consumable-plate technique may be combined with wire feeding to furnish part of the filler metal.

b. Regardless of the number of electrodes used, the machines have constant-speed wire feeders with separate motors and drive rolls for each electrode. Vertical motion of the machine is provided by a motor, which engages a pinion turning on a rack fastened to a vertical mast. The mast can be extended to any height. The vertical travel may be actuated either manually or automatically. Automatic control comes from contact of the molten slag with a probe in one of the copper shoes. Manual control is by a variable-speed motor.

c. The wire-drive motors are usually mounted on a motorized oscillating table. This table permits varying the speed of oscillation and the dwell time at the ends of the stroke. The operator usually controls the speed of the wire drive. This permits him to control the current by varying the wire speed.

d. Welding power generally comes from a single-phase a-c transformer. A separate transformer is used for each electrode. Direct-current power sources may also be used. The operator controls the open-circuit voltage and the amount of slope for each transformer by switches on the control panel. When plate electrodes are used, power sources generating up to 9000 amps and 50 volts may be used. It is often desirable to use three-phase transformers with three plate electrodes, one connected to each phase. The power source should provide at least 200 amp/in.^{2} of electrode cross section.

166. QUALITY ASSURANCE

a. General. Welding variables in the electroslag process can have a significant effect on the quality of welds. They can affect penetration, fusion, and cracking. Several of these factors are discussed in the following paragraphs.

b. Form Factor. The manner in which a weld solidifies has a great influence on its resistance to cracking. And the manner of solidification is, in turn, controlled by the shape of the molten-weld pool. This shape can be best expressed by the term form factor. This is the ratio of the total width of the weld pool to its maximum depth. Welds with a high form factor (shallow depth with respect to width) will solidify with grains meeting at an acute angle and will have a high resistance to cracking. Welds with a low form factor, on the other hand, will solidify with the grains meeting at an obtuse angle and will have low crack resistance. Form factor is controlled to a large extent by welding variables.

c. Welding Current. An increase in welding current serves to increase the depth of the weld pool. At low current levels, it will also increase weld width; however, above 400 amp, with a 1/8-inch electrode, an increase in current reduces width. In either case, increasing the current will decrease the form factor. With 1/8-inch electrodes, welding currents of 550 to 650 amps are usually used. This current may have to be reduced to around 400 amps for highly crack-sensitive materials and can be raised to as much as 900 amps for crack-resistant materials.

d. Welding Voltage. Welding voltage is the primary means for controlled depth of fusion in the electroslag process. An increase in voltage increases penetration into the base metal and the width of the weld. By increasing the width it also increases the form factor and thus improves cracking resistance. Voltage also has an effect on the stability of the operation. When voltage is too low, short circuiting or arcing to the weld pool will occur. If voltage is too high, slag spatter and arcing across the top of the slag pool may result. Generally, 40 to 55 volts are used for 1/8-inch-diameter electrodes.

e. Electrode Extension. Electrode extension refers to the distance between the slag surface and the end of the contact tip. An increase in electrode extension increases electrode melting rate and the deposition rate. This in turn reduces weld width and hence form factor. This effect is due to the resistance heating of the electrode by the welding current. Initially, an increase in electrode extension stabilizes the process. Eventually though, it leads to instability because of melting of the electrode at the slag surface. A long extension also makes it more difficult to locate the electrode in the weld groove. An extension of about 3 inches is generally best for a 1/8-inch electrode.

f. Electrode Oscillation. Electrode oscillation is necessary for weld-joint thicknesses greater than about 1-1/2 inches. An increase in

the speed of oscillation will increase the weld width and form factor. It is also necessary to have a dwell period at the end of each oscillation to obtain complete fusion at the weld corners. This period may range from 2 to 7 seconds, but is generally about 5 seconds.

g. Slag Depth. The slag pool must be deep enough to allow the electrode to extend into it and to permit current to flow by conductivity rather than arcing. However, if it is too deep, it will reduce the depth of fusion and hence the form factor. This is because a given amount of energy will be distributed over a greater area as the slag depth increases. This will reduce the temperature of the slag bath. Generally, increased currents will allow deeper slag pools. Maximum slag pool depth is about 1-1/2 to 2 inches.

h. Number of Electrodes. With a given number of electrodes, the weld width decreases as material thickness increases. If this is continued, a point will be reached where weld width becomes less than the groove opening and fusion is impossible. At this point, the number of electrodes must be increased. In general, one electrode can be used for material up to 4 inches thick, two electrodes up to 10 inches, and three electrodes up to 18 inches.

i. Weld Defects. Table XXII shows some of the defects that may occur in electroslag welds and their causes. These are generally associated with carbon and low-alloy steels.

TABLE XXII. ELECTROSLAG WELDING DEFECTS AND THEIR CAUSES

Location	Defects	Cause
Weld	Porosity	Gases, inadequate deoxidizers.
	Non-metallic inclusions	Excessive slag pool depth. High thermal conductivity base metal. Deep cuts in flame cut faces. Unfused non-metallics from plate laminations.
	Cracking	Carbon content. Form factor. Weld stopping.
Heat Affected Zone	Cracking	Rapid cooling of heat affected zone. Incomplete penetration at face. High restraint. Composition of base metal. Excessive slag pool depth.
	Undercutting	Excessive dwell time. Inadequate cooling of shoes. High voltage.
Fusion Line	Lack of fusion	Low voltage. High wire feed rate. Excessive slag pool depth. Misalignment of electrode(s). Excessive electrode-to-shoe distance. Inadequate dwell time. Excessive oscillation speed.

Section IV. VERTICAL SUBMERGED-ARC WELDING

167. DEFINITION

Vertical submerged-arc welding is a process variation of standard submerged-arc welding. Like other vertical welding processes, such as electrogas and electroslag, the weld is made between two plates in the vertical position. Welding is done in a cavity formed by two solid copper blocks, clamped on either side of the joint and running the full length of the joint. A flux-coated, consumable wire-guide tube is centered in this cavity. Wire is fed through this tube into the arc. The end of the electrode, the arc, and the molten weld puddle are shielded by a pool of molten flux. This flux pool is constantly replenished by flux from the consumable wire-guide tube. The process is shown schematically in Figure 59.

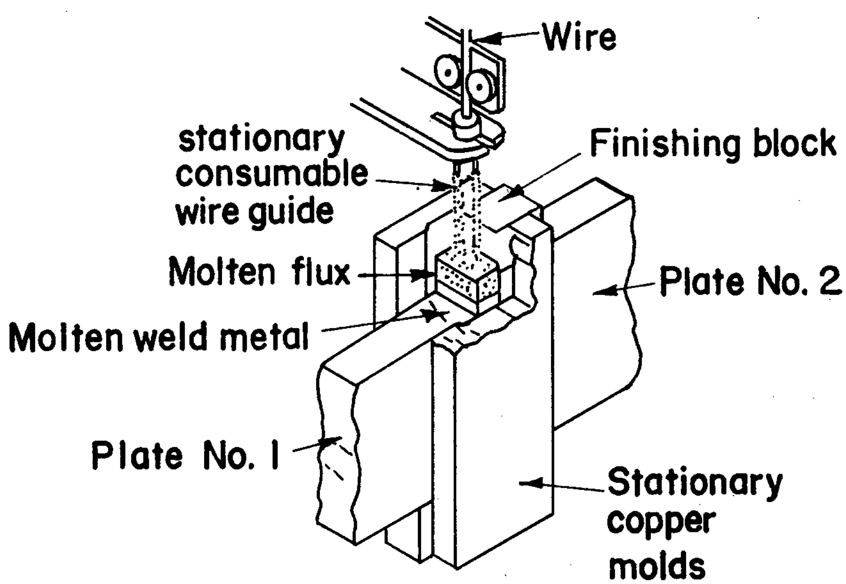


FIGURE 59. SCHEMATIC REPRESENTATION OF VERTICAL SUBMERGED-ARC WELDING PROCESS

168. IMPORTANCE AND USES

a. The vertical submerged-arc process is relatively new, and therefore has not been used extensively as a production tool. However,

it should be applicable in the same areas as electrogas and electroslag for plate thicknesses 6 inches and under. The choice of process will depend on the process requirements as governed by the welding codes or specifications which apply to a given application. Economics and equipment availability must also be considered.

b. The vertical submerged-arc process is adaptable for welding 5/8 to 6-inch-thick steel plate. Plates up to 8 feet in length have been welded. The process has been used primarily for butt joints, but is adaptable to tee and corner joints as well.

c. Vertical submerged-arc welding is a single-pass process and offers the following advantages over flat-position welding:

(1) Deposition speeds up to three times greater

(2) Reduced joint preparation

(3) Greater fit-up tolerance

(4) Cleaner weld metal, free of porosity and slag inclusions

(5) Lower tendency toward cracking when welding hardenable steels

(6) Less weld-joint distortion

169. THEORY

a. With vertical submerged-arc welding, a single-pass butt weld is made using single or multiple electrodes, depending on the thickness of the plates being welded. The joint edges are square and are placed approximately 1 inch apart. The top and bottom of the joint are fitted with starting and runoff tabs, and copper blocks are clamped on each side of the joint, running the full length of the joint. The weld is made by extending a flux-coated, consumable wire-guide tube into the cavity and charging a small amount of flux into the starting portion of the joint. Wire is fed through the contact tube and an arc is initiated at the bottom of the joint. The flux charge is melted and forms a 3/4 to 1-1/2-inch protective blanket over the weld. As welding progresses, the wire-guide tube melts at the surface of the flux pool and is added to the weld as filler metal. Part of the flux solidifies at the surface of the copper shoes, but is replaced by the addition of flux from the wire guide as it melts. When the flux reaches the top of the runoff tab, the weld is completed.

170. MULTI-WIRE WELDING

a. For plates thicker than about 2-1/4 inches, additional electrode wires are needed. The additional electrodes have individual wire-guide tubes. Plates up to about 4-1/2 inches thick can be welded with two wires, and plates to about 6-1/4 inches thick, with three wires. The distance between plates remains at about 1 inch with any number of wires.

b. Vertical submerged-arc welding uses the same solid electrode wires normally used with conventional submerged-arc welding. Wires from 3/32 to 5/32-inch diameter can be fed through the wire-guide tube. When selecting the wire, the chemical composition of both the base metal and the wire-guide tube must be considered. Generally, the final weld metal consists of about 40 percent from the base metal, a minimum of 40 percent from the wire, and a maximum of 20 percent from the wire-guide tube.

c. The welding rate in vertical submerged-arc welding is a direct function of the wire-feed speed. Using a constant-potential power supply, the wire is fed at a constant speed, and the welding rate remains constant as long as the plate spacing is the same. When the wire-feed speed is set, the welding current automatically adjusts to melt the wire at the rate it is being fed. The wire-guide tube melts at the rate of weld progression.

d. The consumable wire-guide tube acts as a current-carrying conductor for the wire, and its flux coating insulates the tube to prevent short circuits. Welds are made with one-piece tubes of the proper length. For particularly long welds, it may be necessary to join several short lengths of tube. For welds over 3 feet long, or for multiple-wire welding, consumable spacers can be used to help align the tube.

171. EQUIPMENT AND CONTROLS

a. The basic equipment needed for vertical submerged-arc welding is a heavy-duty wire feeder, a wire-feed control, power supply, and copper shoe blocks. Both fixed and portable equipment are available.

b. The basic electrode feeder and slide assembly can be mounted on a fixed station, as shown in Figure 60, and the material to be welded placed under it. The feeder will remain at a fixed elevation for any given application, but may be raised or lowered to accommodate different plate heights. The electrode feed control is a standard submerged-arc welding unit. Because the copper shoes are stationary, there is no need for a vertical lift mechanism and control device.

c. Vertical submerged-arc welding is usually operated from a direct-current, constant-potential power source. This offers the following advantages:

(1) A simple and inexpensive electrode-feeder control system can be used.

(2) Weld conditions are easy to establish and maintain.

(3) The tendency toward arcing between the consumable electrode guide and surface of the flux pool is reduced by the use of low, open-circuit-voltage power equipment.

d. The power supply should have a capacity of at least 1000 amperes at 40 volts and a 100 percent duty cycle. For multiwire welding, the maximum requirement is 700 amperes per wire. Power supplies having drooping volt-ampere characteristics can also be used. With this type of power, however, the wire-guide tube can submerge itself in the flux pool unless weld speed is closely controlled. This can result in poor voltage stability and flux spatter.

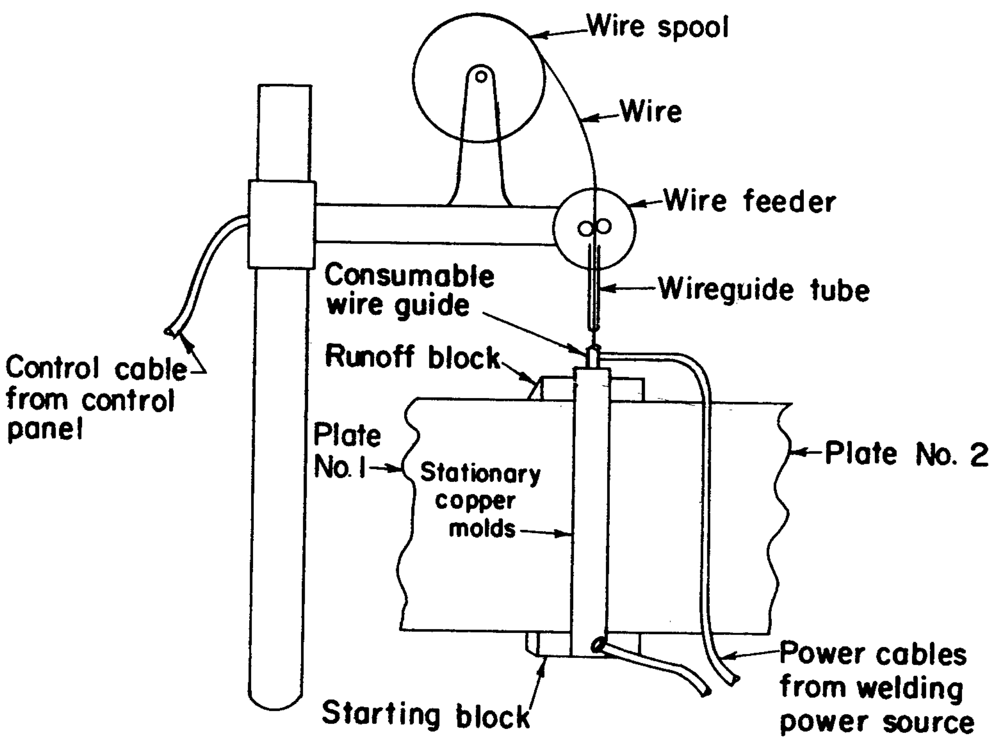


FIGURE 60. VERTICAL SUBMERGED-ARC WELDING EQUIPMENT

CHAPTER 8

STUD WELDING

Section I. INTRODUCTION

172. DEFINITION

a. Stud welding is an arc-welding process for joining a metal stud or similar part to a workpiece. In electric-arc stud welding, fusion is produced by an electric arc between the parts as they are brought together under pressure. Partial shielding for the process may be obtained by the use of a ceramic ferrule surrounding the stud. Additional shielding effects are obtained by the use of flux contained in a recess at the welding end of steel studs and by inert-gas shielding of aluminum studs. In capacitor-discharge stud welding, fusion is produced simultaneously over the entire area of the abutting surfaces by the heat obtained from an arc produced by a rapid discharge of stored electrical energy. Pressure is applied during or immediately following the electrical discharge. Because of the short welding time, neither flux nor shielding of any kind is normally required in capacitor discharge stud welding.

b. There are actually three basic stud-welding processes. Electric-arc stud welding is the most versatile and most widely used of these. Capacitor-discharge stud welding is particularly suited for welding small-diameter fasteners to thin or difficult-to-weld base metals. A third process, known as drawn-arc capacitor discharge, has recently come into use. The drawn-arc capacitor-discharge process is a combination of electric-arc and capacitor-discharge stud welding.

c. The first and third of these processes are similar in many respects to manual metal-arc welding. The primary difference is in automatic control of arc establishment, welding time, and the final plunge of the stud to complete the weld. Thus, operator inconsistencies in the welding process are almost completely eliminated. The stud is held in a portable, pistol-shaped welding torch called a stud gun. It is positioned by the operator, who then actuates the unit by pressing a trigger switch. Usually, the weld is completed in less than 1 second by the stud gun and its controller.

d. Electric-arc stud welders use a d-c power source, such as a motor generator or transformer rectifier. Capacitor-discharge stud welders use a low-voltage storage system where the energy for welding is stored in capacitors.

173. IMPORTANCE AND USES

a. The stud-welding process is widely accepted in the metalworking industries. It is now being used quite extensively in such fields as shipbuilding, railroads, construction, equipment manufacture, automotive, and boiler manufacture. The use of stud welding allows designers to reduce the thickness of plates and to eliminate the heavy bosses and flanges normally needed to obtain sufficient tap depth to secure cover plates and bearing caps. These lighter weight designs not only save material but reduce the amount of manual welding and machining needed to join parts. Recommended uses for each of the three stud-welding processes are listed in Table XXIII.

b. Table XXIV shows minimum recommended plate thicknesses for stud welding. These thicknesses are sufficient to permit welding without burnthrough or excessive distortion. In general, the minimum allowable ratio of plate thickness to stud-weld base diameter is 1 to 5. However, to develop full fastener strength, the minimum should be 1 to 3. Fasteners can be stud welded anywhere without regard for bolt hole-to-edge distance. Also, it is not necessary to consider what may be on the back side of the plate. The design will be leakproof without rework because of the absence of drilled holes and boss or pad weldments.

c. With capacitor-discharge stud welding, weld penetration is slight. This allows thin metals to be welded without burnthrough and also allows welding of dissimilar metals with acceptable metallurgical results. Table XXV shows the welding results of various stud and base-plate combinations. The electrical resistivity or the melting temperature of the part to be joined make little difference so long as it is a good conductor of electricity.

d. Since each stud must have a special tip projection at the weld base, the types and shapes of fasteners that can be welded with capacitor-discharge welding are limited. However, fasteners of all types and shapes can be welded with drawn-arc capacitor-discharge equipment. Here, the stud does not require a special tip projection. Stud diameters from 1/8 to 5/16 inch are now being welded in ferrous and nonferrous materials. See Table XXIII.

Section II. PRINCIPLES OF OPERATION

174. ELECTRIC-ARC STUD WELDING

a. Electric-arc stud welding involves the same basic principles that any of the other arc-welding processes do. There are two steps in applying

TABLE XXIII. PROCESS SELECTION CHART

	Electric-Arc Stud Welding	Drawn-Arc Capacitor-Discharge Stud Welding	Capacitor-Discharge Stud Welding
Fastener Shape			
Round	A	A	A
Square	A	A	A
Rectangular	A	A	A
Irregular	A	A	A
Fastener Diameter or Area			
1/16 to 1/8 in. dia.	C	A	A
1/8 to 1/4 in. dia.	A	A	A
1/4 to 1/2 in. dia.	A	D	D
1/2 to 1 in. dia.	A	D	D
Up to 0.05 sq. in.	C	A	A
Over 0.05 sq. in.	A	D	D
Fastener Material			
Carbon steel	A	A	A
Stainless steel	A	A	A
Alloy steel	B	C	C
Aluminum	B	A	A
Brass	C	A	A
Plate Material			
Carbon steel	A	A	A
Stainless steel	A	A	A
Alloy steel	B	C	A
Aluminum	B	A	A
Brass	C	A	A
Plate Thickness			
Under 0.015 in.	C	B	A
0.015 to 0.062 in.	C	A	A
0.062 to 0.125 in.	B	A	A
Over 0.125 in.	A	B	B

TABLE XXIII. PROCESS SELECTION CHART (CONT)

	Electric-Arc Stud Welding	Drawn-Arc Capacitor-Discharge Stud Welding	Capacitor-Discharge Stud Welding
Strength Criteria			
Heat effect on exposed surfaces	B	A	A
Weld fillet clearance	B	A	A
Strength of fastener governs	A	A	A
Strength of plate governs	A	A	A

A - Applicable without special procedures, equipment, etc.
B - Applicable with special techniques or on specific applications which justify preliminary trials or testing to develop welding procedure and weld technique.
C - Limited application.
D - Not recommended. Welding methods not developed at this time.

TABLE XXIV. MINIMUM RECOMMENDED PLATE THICKNESSES FOR STUD WELDING

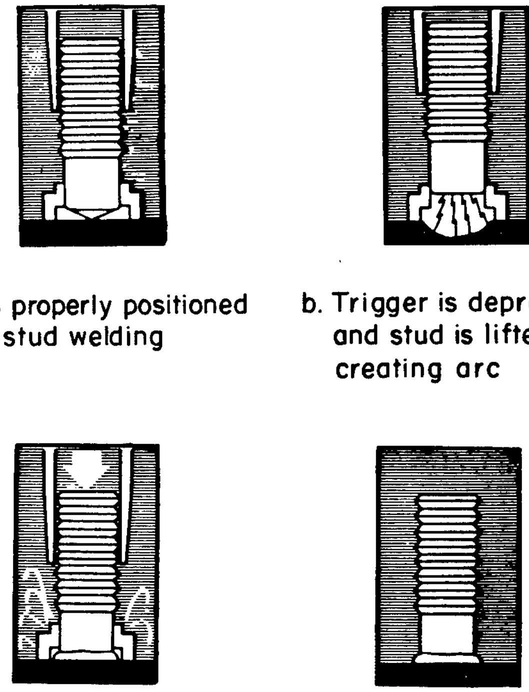
Weld Base Diameter, in.	Plate Thickness, in. (gage)
0.187	0.0359 (20)
0.250	0.0478 (18)
0.312	0.0598 (16)
0.375	0.0747 (14)
0.437	0.0897 (13)
0.500	0.1196 (11)
0.625	0.148 (9)
0.750	0.164 (8)
0.875	0.187
1.000	0.250

TABLE XXV. CAPACITOR DISCHARGE STUD AND BASE MATERIAL COMBINATION

Material Base	Stud Material: Mild Steel, C-1008, C-1010	Stainless Steel, 304, 305	Aluminum, 1100, 5086	Brass, 65-35, 70-30
Mild Steel (C-1008 to C-1030)	Excellent	Excellent		Excellent
Medium Carbon Steel (C-1030 to C-1050)	Limited	Limited		Limited
Galvanized Steel, (Duct--"Q" Decking)	Excellent	Excellent		
Structural Steel	Excellent	Excellent		Excellent
Stainless Steel (405) (410) (430) 300 Series except 303	Excellent	Excellent		Excellent
Lead Free Brass, Electrolytic Copper, Lead Free Rolled Copper	Excellent	Excellent		Excellent
Most Aluminum alloys of the 1000, 3000, 5000 and 6000 series			Excellent	
Zinc Alloys (Die cast)	Limited	Limited	Excellent	Limited

the process: (1) developing heat by drawing an arc between the stud and the plate to which it is to be welded and (2) bringing the two pieces into intimate contact when the proper temperature is reached. The weld is made by loading a stud into the chuck of the gun, placing the ferrule (also known as a shield) over the end of the stud, and positioning the gun for welding. The automatic welding sequence is shown in Figure 61.

b. This triggering energizes a solenoid coil within the body of the gun, which lifts the stud and creates an arc. The arc forms molten pools on the plate and the end of the stud. A preset control unit times the arc duration. The welding current automatically shuts off at the end of this period, de-energizing the gun and allowing the mainspring of the gun to plunge the stud into the molten pool on the plate. This completes the weld The gun is pulled from the stud and the ferrule is knocked off.



a. Gun properly positioned for stud welding

b. Trigger is depressed and stud is lifted, creating arc

c. Arcing period is completed and stud is plunged into molten pool of metal on base plate

d. Gun is withdrawn from stud and ferrule is removed

FIGURE 61. AUTOMATIC WELDING SEQUENCE

c. The time required for a complete weld cycle varies from about 8 cycles for a 10-gage pin to 55 cycles for a 7/8-inch-diameter stud (a cycle equals 1/60 sec). The size of the stud and such other factors as working conditions will affect application rates.

d. For welding of steels, the welding end of the stud is usually recessed to hold a quantity of flux. For aluminum welding, however, plain studs are used with an argon or helium shield.

175. CAPACITOR-DISCHARGE STUD WELDING

In capacitor-discharge stud welding, weld energy is stored at a low voltage in high-capacitance capacitors. The stud for capacitor-discharge welding and the welding sequence are shown in Figure 62. Each stud has a

small, specially engineered projection or tip at the weld base. In operation, this projection is brought in contact with the base material, and pressure is applied by means of a spring or air pressure. The closure of contact points completes the weld circuit, and the stored energy is discharged through the projection at the base of the stud. The stud projection presents a high resistance to the stored energy and rapidly disintegrates. This creates an arc and heats the surfaces to be joined. During this arcing, the pieces are brought together by the action of the spring or air pressure. When contact is made, fusion takes place and the weld is completed. It is possible to produce a high-intensity arc of such short duration (about 0.006 sec) that the heat effect upon the mated parts is purely superficial. Only a surface layer a few thousandths of an inch in thickness on each part reaches a molten state. Because of this short welding time, neither flux nor shielding of any kind is needed.

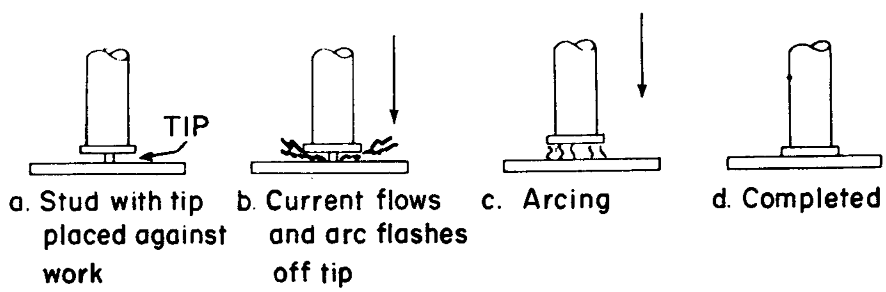


FIGURE 62. SCHEMATIC DIAGRAM ILLUSTRATING STEPS IN CAPACITOR DISCHARGE STUD WELDING

176. DRAWN-ARC CAPACITOR-DISCHARGE STUD WELDING

In drawn-arc capacitor-discharge stud welding, arc initiation is obtained in a manner similar to electric-arc stud welding, as shown in Figure 63. In this manner, the need for a tip projection on the weld end of the stud is eliminated. Weld time varies from 6 to 15 milliseconds. Flux is not required, but shielding gases may be used in aluminum welding.

177. EQUIPMENT AND CONTROLS

a. General. Electric-arc stud-welding equipment compares in portability and ease of operation with manually shielded metal-arc welding equipment. The basic equipment necessary is:

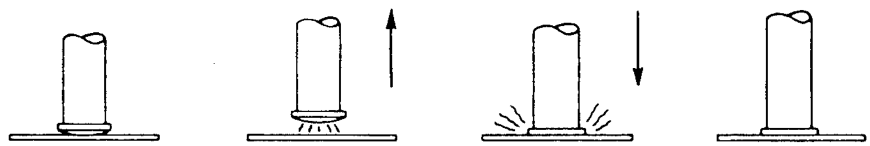


FIGURE 63. SCHEMATIC DIAGRAM ILLUSTRATING STEPS IN DRAWN-ARC CAPACITOR DISCHARGE STUD WELDING

(1) Stud welding gun--either portable or fixed (production gun)

(2) A control unit to control the time of the current flow

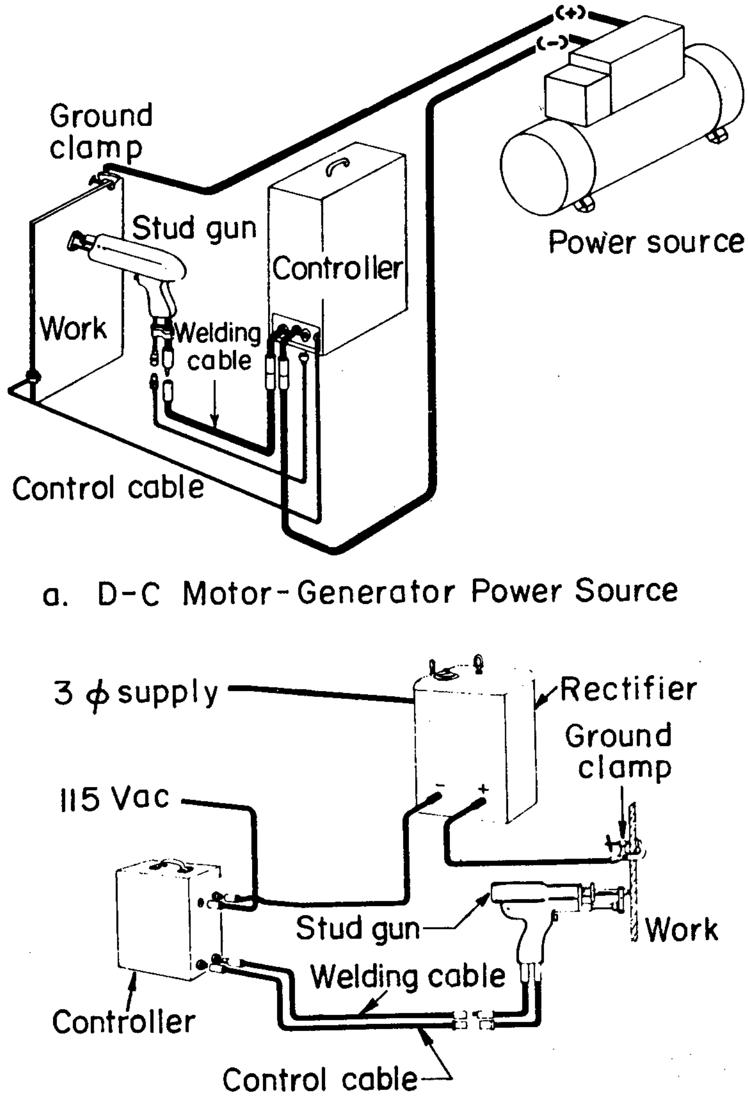
(3) A power source.

Stud-welding guns and control units are shown in Figure 64.

b. Types of Stud-Welding Guns. Stud-welding guns can be either portable or fixed, but either kind operates on the same principle. The portable gun resembles a pistol and weighs from 4-1/2 to 9 pounds. The smaller guns are used for studs from 1/8 to 1/2 inch in diameter and the larger tools for studs through 1-1/4 inch in diameter. Basically, the gun consists of a body, mechanism, chuck holder, adjustable support for furrule holder, and calbes. Fixed guns are located on automatic positioning devices. They are usually air operated and electrically controlled. Locating fixtures are used to position the work under the gun and tolerances of ±0.005 inch on location and ±0.010 inch on height are possible.

c. Control Units.

(1) The control unit consists of a contactor suitable for interruption of the weld current and a timing device. Other components are added to provide for proper operation. The weld timer is easily adjusted and is graduated in terms of cycles of a 60-cps input. The control unit maintains the proper weld time for the size stud being welded. This time may vary from 3 to 120 cycles. Some control units will also control the exact heat energy required for the weld, regardless of power fluctuations. There are two sizes of control units: a smaller for welding studs up to 1/2 inch in diameter and a larger for studs of larger diameter.



a. D-C Motor-Generator Power Source

b. Rectified A-C Power Source

FIGURE 64. SCHEMATICS OF POWER AND CONTROL CIRCUIT FOR STUD WELDING WITH D-C MOTOR-GENERATOR POWER SOURCE AND RECTIFIED A-C POWER SOURCE

(2) The equipment and controls for capacitor-discharge and drawn-arc, capacitor-discharge stud welding are basically the same. Portable capacitor-discharge welding requires two basic pieces of equipment with interconnecting cables. one is the gun and the other is the control and power source. The gun holds and positions the stud for welding and, through

the trigger or switch, controls the power source for discharging and charging the capacitors. It has a variable chuck, which can accommodate different diameters and shapes of studs. The control and power source provides the welding current and also contains the necessary circuitry for charging the capacitors. By varying the voltage on the capacitors, variable-discharge currents can be obtained. The machine automatically controls charging and discharging currents.

(3) Stationary equipment for capacitor-discharge stud welding is also available. Very high production rates are possible with this equipment, depending on the amount of automation in the fixturing and the feeding of studs and parts. As many as 60 welds/min have been made with stud locations controlled to a tolerance as close as 0.005 inch.

d. Power Sources. Stud welding must be done using a d-c power source. This may be a rotating motor-generator type, a rectifier type, or a battery unit. The general characteristics desired in a stud-welding power source are:

(1) High terminal voltage in the range of 70 to 100 volts d-c open circuit

(2) A drooping-voltage characteristic such that 25 to 35 volts d-c appears across the arc at maximum load

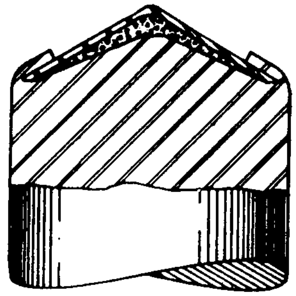
(3) A rapid current-rise time

(4) High current capacity for a relatively short time. The current requirements are higher and the duty cycle is much less in stud welding than in other types of welding.

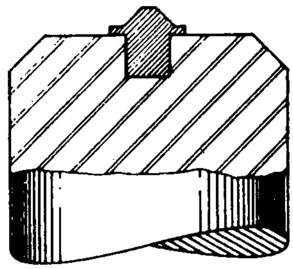
Section III. STUDS AND FERRULES

178. STUDS

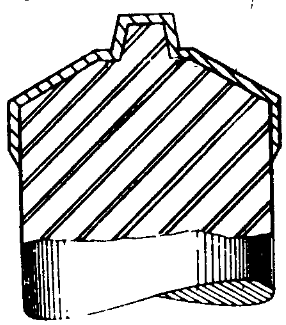
a. Studs being welded commercially today range from 1/8 inch to 1-1/4 inches in weld-base diameter. Many steel studs have the welding end recessed to contain a quantity of flux within, or permanently affixed to, the end of the stud (Figure 65). The flux acts as an arc stabilizer, and together with the shielding effect of the ferrule protects the molten metal from oxidation during welding. Low-carbon steel is a standard stud material. Many specifications require a minimum tensile strength of 60,000 psi,



a. Granular Flux



b. Solid Flux



c. Flux Coating

FIGURE 65. THREE METHODS OF CONTAINING FLUX ON END OF A WELDING STUD

a minimum yield point of 50,000 psi, and 20 percent minimum elongation in 2 inches. A low-carbon steel may be used where irregularly shaped studs are made by the cold heading process. Work hardening or drawing of the stud material will increase the tensile and yield strengths and lower the ductility. Annealing, on the other hand, will decrease the tensile and yield strengths, but will greatly increase ductility.

b. Stud Types. A wide variety of stud styles are available for use with electric-arc stud welding. They may be threaded fasteners, plain or slotted pins, internally threaded fasteners, flat fasteners with rectangular cross section, header pins with various upsets, or cotter keys. The stud

stock can be round, square, or rectangular, but rectangular studs are difficult to weld when the width of the stud is more than five times its thickness. Limitations on stud design are listed below.

(1) Welds can be formed on only one end of a stud

(2) The stud shape must be such that a ferrule can be produced that fits the base well

(3) The cross-sectional area of the stud weld base must be within the range of available stud-welding equipment

(4) The stud must be shaped so that it can be chucked or held for welding.

c. Stud Design Considerations.

(1) During welding, a portion of the stud is burned off so that the finished length is less than the original length of the stud. The amount of burn-off depends on the diameter of the stud and to some degree on the application. Typical burn-off values for various stud diameters are shown in Table XXVI.

TABLE XXVI. TYPICAL STUD BURN-OFF* VS. STUD DIAMETER

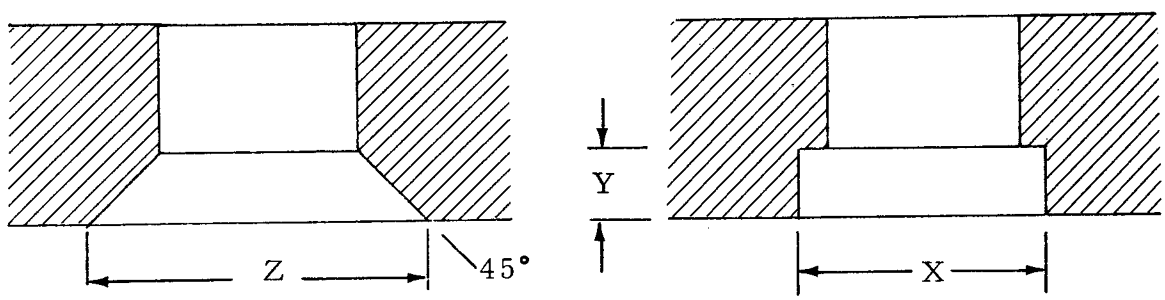
Stud Diameter, in.	Approximate Burn-Off, in.
1/8 to 1/2	1/8
5/8 to 7/8	3/16
1 and over	1/4

*Based on original length.

(2) The design of the ferrule controls the dimensions of the weld fillet formed around the base of the stud. The fillet diameter is generally larger than that of the stud. Thus, in designing the mating parts, some consideration must be given to this diameter. The joints are strong and pressure tight and can be made without access to the back side of the base material.

Table XXVII shows dimensions of standard counterbores and countersinks needed to provide fillet clearance for full-diameter and pitch-diameter weld-base studs. Additional methods of accommodating weld fillets are shown in Figure 66.

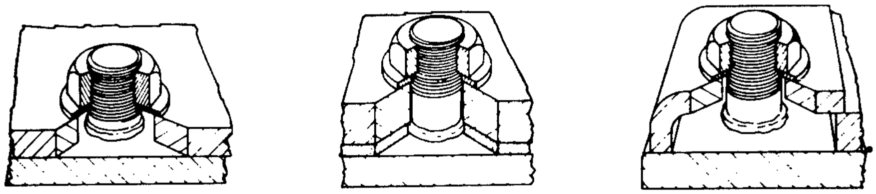
TABLE XXVII. MINIMUM COUNTERBORE AND COUNTERSINK DIMENSIONS TO ACCOMMODATE WELD FILLETS



X = Counterbore Diameter, Y = Counterbore Depth, Z = Countersink Diameter

Stud Diam., inch	Full Weld Base Threaded and Unthreaded Studs, inch			Pitch Diam. Weld Base Studs, inch			Standard Studs Having Slightly Reduced Weld Base, inch		
D	X	Y	Z	X	Y	Z	X	Y	Z
3/16	0.325	0.100	0.528	–	–	–	–	–	–
1/4	0.437	0.125	0.687	0.375	0.094	0.562	–	–	–
5/16	0.500	0.125	0.750	0.469	0.109	0.593	–	–	–
3/8	0.593	0.125	0.843	0.531	0.109	0.750	0.500	0.125	0.730
7/16	0.656	0.187	1.031	0.594	0.125	0.844	0.593	0.125	0.844
1/2	0.750	0.187	1.125	0.656	0.187	0.968	0.656	0.187	0.968
5/8	0.875	0.218	1.312	0.812	0.218	1.250	0.750	0.187	1.125
3/4	1.125	0.312	1.687	0.938	0.250	1.437	–	–	–
7/8	1.250	0.375	1.950	1.062	0.312	1.687	–	–	–
1	1.437	0.437	2.250	1.213	0.375	1.968	–	–	–

Note: Dimensions are subject to change because ferrule or stud design modifications. It is therefore suggested that test welds be made and checked.



a. Oversize Clearance Holes b. Gasket Material c. Dog

FIGURE 66. METHODS OF ACCOMMODATING STUD FILLETS

(3) A tensile-torque chart is presented in Table XXVIII. This shows the expected yield load of welded assemblies and can be used to assist in engineering such assemblies. It lists the load in tension at which yielding will occur for various thread diameters and the corresponding weld-base diameters. It also shows the wrench torque (applied to a nut, washer, and spacer) to develop this load. The data are based upon 60,000-psi yield-strength steel. It should be remembered that several variables affect the torque-tension relation, including steel strength, thread finish, lubrication, washer type, and stud hardness. For this reason, a stud should never be used at its yield load. A factor of safety must be determined by the user, but generally studs are used at no more than 60 percent of yield.

179. FERRULES

a. A ceramic ferrule must be used for each stud in electric-arc stud welding. This is placed over the stud and held in position by a suitable grip or holder. The functions performed by the ferrule during welding are:

(1) It concentrates the heat of the arc in the weld area

(2) It reduces oxidation of the molten metal during welding by restricting passage of air to the weld area

(3) It confines the molten metal to the weld area

(4) It prevents contamination of the weldment through charring of the material

(5) It eliminates the need for a welding hood by protecting the eyes of the operator from the arc. (Safety glasses are still recommended, however.)

TABLE XXVIII. TENSILE-TORQUE* CHART - STUD SIZE #10-24 TO 1-1/8 IN. -7

Stud Stud Thread Size	Weld Base Dia Min, in.	Torque, ft lbs	Tensile Yield Load, lbs
10 - 24 NC	0.158	3.1	1010
10 - 32 NF	0.165	3.5	1200
1/4 - 20 NC	0.217	7.8	1885
1/4 - 28 NF	0.217	8.9	2150
5/16 - 18 NC	0.271	15.0	3100
5/16 - 24 NF	0.271	16.5	3450
3/8 - 16 NC	0.312	28.0	4600
3/8 - 24 NF	0.312	32.0	5200
7/16 - 14 NC	0.375	45.0	6250
7/16 - 20 NF	0.375	51.0	7100
1/2 - 13 NC	0.437	69.0	8400
1/2 - 20 NF	0.437	79.0	9500
5/8 - 11 NC	0.500	139.0	13500
5/8 - 18 NF	0.500	157.0	15200
3/4 - 10 NC	0.625	250.0	20000
3/4 - 16 NF	0.625	275.0	22000
7/8 - 9 NC	0.750	390.0	27500
7/8 - 14 NF	0.750	440.0	30000
1 - 8 NC	0.875	575.0	35000
1 - 14 NF	0.875	650.0	40000
1-1/8 - 7 NC	1.000	775.0	46000
1-1/8 - 12 NF	1.000	860.0	50000

*Torque and tensile values based on 60,000 psi yield strength steel.

b. The ferrule is generally cylindrical in shape and has a flat bottom for welding to flat surfaces. Its base is serrated to form vents, and it is shaped internally to mold the molten metal around the base of the stud, forming a weld fillet. There are specially designed ferrules for welding at angles and welding to contoured surfaces. The bottom face of these ferrules will match the required contour.

Section IV. QUALITY ASSURANCE

180. QUALITY ASSURANCE

a. There are several factors in regard to stud-welding equipment that may produce variations in the weld. Through precontrol and maintenance of these factors, weld quality can be maintained. Some basic rules to follow are:

(1) Have sufficient welding power for the size of stud being welded

(2) Always use straight polarity--electrode (gun) negative, ground or work positive. (For aluminum-stud welding, reverse polarity is used.)

(3) Always clean the work surface at the point of ground connections to ensure a good ground.

(4) Use welding cables of sufficient capacity and insure good connections

(5) Use correct accessories and ferrules

(6) Center the stud so that it extends approximately 1/8 inch beyond the ferrule

(7) Hold the gun perpendicular to the work

(8) Clean the work surface of paint, rust, and heavy mill scale

(9) Keep all stud-welding equipment properly cleaned and maintained

(10) Make test welds before starting a job.

b. It is quite important to select the proper weld time and weld current. These will vary with the diameter of the stud. The smaller the stud diameter, the less weld time and current required. The importance of weld time and weld current is in obtaining the proper heat, or watt cycles, for a given stud diameter. Increasing the weld current will compensate for too low a weld time, but such adjustments should be held within limits.

c. The current output of a generator at a given setting may vary, depending upon the size and length of cables used. In order not to penalize

the power source in this manner, it is very important to select the proper size and length of welding cable. Figure 67 indicates the effect this size and ~~length can~~ have on current. Power was kept at the maximum setting of the generator for all varieties of cable during the tests made to obtain these curves.

181. STUD LOCATION

The method chosen for locating studs depends on how the stud is to be used and how accurately it must be located. Special locating fixtures and a fixed-type stud-welding gun may be used where extreme accuracy in location is required. When using a portable gun, there are several methods for locating the studs. The most common of these is to lay out and center punch the work material, or to center punch through a template. Using this method, the point of the stud is then placed in the center punch mark. Tolerances of ±3/64 inch can be held with this method. Figure 68 shows a method used when a number of pieces are to be stud welded. Here a simple template is used to locate the ferrules. Tolerances of stud location with this type template are ±1/32 in. A tube template may be used where very close stud location and alignment is required. A tube adapter holds the ferrule in a locating bushing in the template. By locating this adaptor the stud is centered. Stud location tolerances of ±0.010 to ±0.015 can be held with this type of template.

182. WELD INSPECTION

a. Welds made using electric-arc stud-welding equipment may be inspected both visually and physically. In visual analysis, the inspector analyzes the build-up of weld metal around the periphery of the stud. A successful inspection depends on proper and uniform analysis of this weld fillet. A satisfactory stud weld with good weld-fillet formation is shown in Figure 69. Several improper welds are shown in Figure 70 together with a description of what is needed to correct them.

b. When a weld is questionable after visual inspection, a physical inspection may be performed with a hammer. This consists of striking the stud until it is bent about 20 degrees off vertical. It is then bent back to the vertical. Studs that fail should be replaced. A short length of pipe may be placed over the stud to avoid damaging it during this test.

c. Because there is neither a steady welding arc nor a weld fillet, quality is more difficult to control in capacitor-discharge stud welding than in electric arc stud welding. The operator cannot see the color of the welding arc or observe the characteristics of a weld fillet in order to distinguish a sound weld. The best method of quality control is destructive

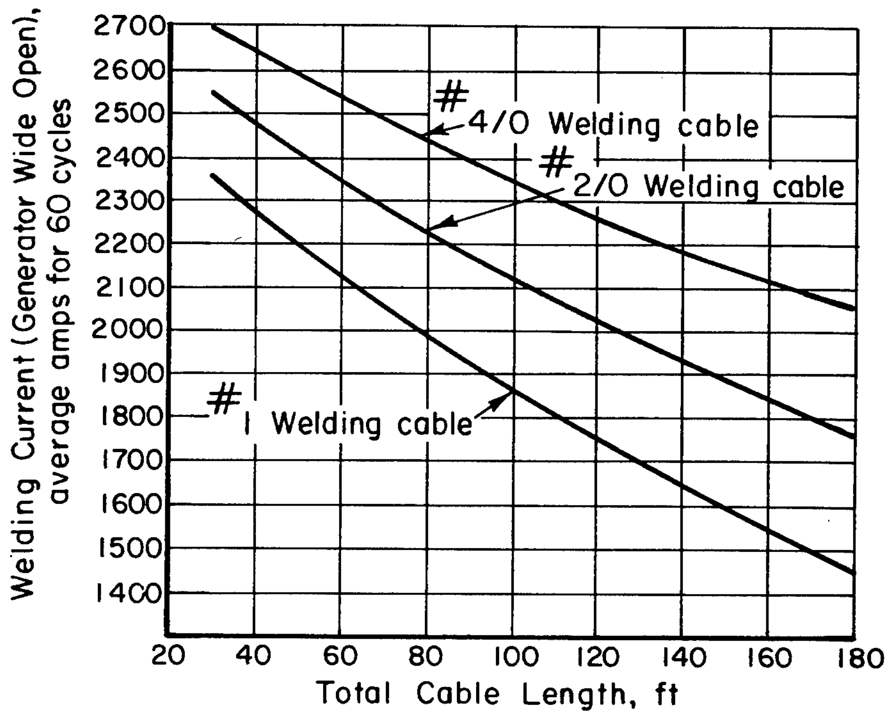


FIGURE 67. EFFECT OF CABLE SIZE ON CABLE LENGTH AND STUD WELDING CURRENT

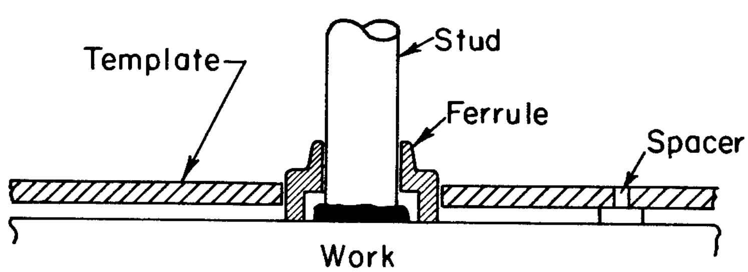


FIGURE 68. SIMPLE TEMPLATE USED TO LOCATE STUDS WITHIN TOLERANCE OF ±1/32 INCH

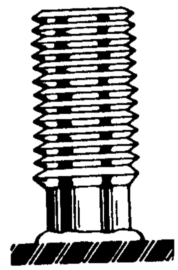


FIGURE 69. SATISFACTORY STUD WELD WITH A GOOD WELD FILLET FORMATION

testing of studs welded to the material to be used in production. This should be by a bend, tensile or torque test. The production run should not begin until satisfactory welds are achieved. Welds should be similarly checked at intervals throughout the run.

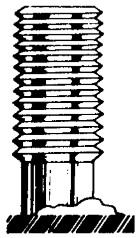
d. The following points should be stressed in assuring satisfactory capacitor-discharge stud welds:

(1) The power source unit should be sufficient for the stud size being welded

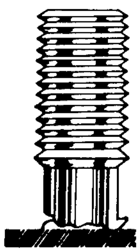
(2) Equipment should be properly maintained and in good operating condition

(3) Cable connections should be tight

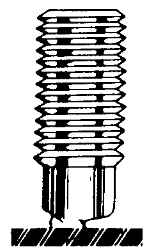
(4) Studs and guns should be properly handled during the welding process.



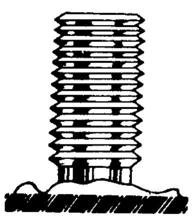
a. Plunge Too Short. Prior to welding, the stud should project approximately 1/8 in. beyond the bottom of the shield



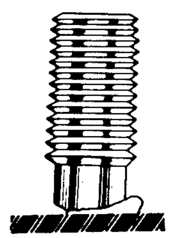
b. Hang-Up. Accessories should be realigned to insure completely free movement of stud during lift and return. Arc length may also require adjustment



c. Low Heat. Ground and all connections should be checked. Power setting and/or time setting should be increased. It may also be necessary to adjust the arc length



d. High Heat. Power setting and/or time cycle should be decreased



e. Poor Alignment. Stud gun should be positioned perpendicular to the work to assure bottoming of the ferrule

FIGURE 70. IMPROPER WELDS AND METHODS OF CORRECTING THEM

CHAPTER 9

OTHER WELDING PROCESSES

Section I. ELECTRON-BEAM WELDING

183. DEFINITION

Electron-beam welding is a welding process in which the heat for fusion is obtained by bombardment of the workpiece by a dense stream of high-velocity electrons. Upon impact, the kinetic energy of these electrons is transformed into heat. Welding with this process is usually performed in a vacuum chamber. While this imposes several limitations, the pure and inert environment allows the metal to be welded without fear of contamination. Figure 71 is a schematic representation of an electron-beam-welding machine.

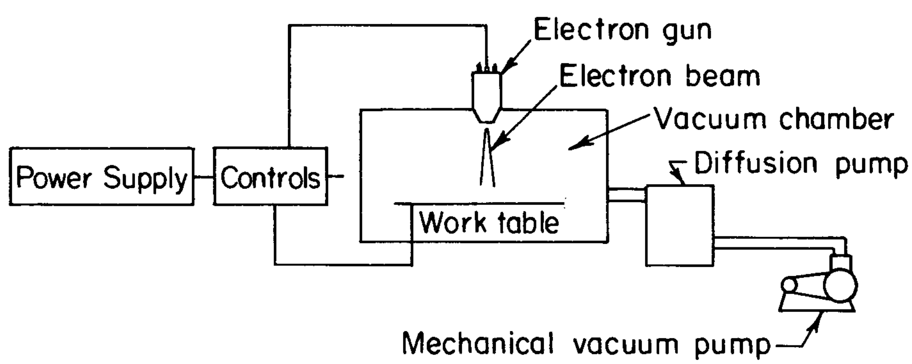


FIGURE 71. SCHEMATIC OF AN ELECTRON-BEAM-WELDING MACHINE

184. IMPORTANCE AND USES

a. The electron beam produces very intense local heat and almost instantly vaporizes a hole through the entire thickness of the parts being joined. This results in extremely narrow, deeply penetrating welds and is the outstanding feature of electron-beam welding. For example, a butt weld only 1/16 inch wide can be made in a 1/2-inch-thick steel plate. Figure 72 compares an electron-beam weld with a gas-tungsten-arc weld in the same material.

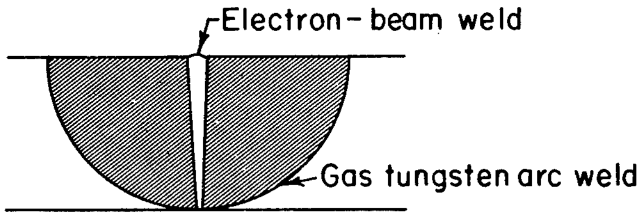


FIGURE 72. COMPARISON OF SIZE AND SHAPE OF ELECTRON-BEAM WELD AND GAS-TUNGSTEN-ARC WELD IN THE SAME MATERIAL

b. The narrow electron-beam weld is made as the hole which the electron beam creates is moved along the joint. The walls of the hole are molten and, as the beam advances, metal flows around the hole and solidifies along the rear side to make the weld. By decreasing the beam intensity, a partially penetrated, but equally narrow, weld can be obtained.

c. Generally, electron-beam welding can be applied to the same areas as automatic gas-tungsten-arc welding. However, it has additional special applications because of its vacuum environment, high energy density, and depth of focus. Some of these applications are listed below.

(1) Reactive and refractory metals whose properties are detrimentally affected by gases such as oxygen, nitrogen, and hydrogen may be welded without introducing these contaminants. These metals include tungsten, molybdenum, columbium, tantalum, zirconium, titanium, and hafnium.

(2) Because distortion is greatly reduced, the welding of precision assemblies and the weld repair of expensive components is practical by electron-beam welding. Metals that normally require preheat--such as molybdenum and high-strength steels--may be electron-beam welded without preheat.

(3) Unstabilized austenitic stainless steels can often be welded without sensitization. It is also possible to weld high-strength steels after heat treatment without lowering tensile strength.

(4) It is possible to make simple butt joints in heavy sections with a single pass. This has been demonstrated for plates up to 6 inches thick.

(5) Multiple welds can be made in a single pass. Honeycomb structures, with external skins separated as much as 3 inches vertically, have been butt welded in a single pass.

(6) Welds that are nonlinear in the vertical plane can be made without adjustment of controls. A sinusoidal rib with an amplitude of 3/4 inch has been joined to a honeycomb skin to form a T-section.

(7) The process may be used to seal parts requiring an internal vacuum.

d. The emphasis on the application of the electron-beam process has passed from exotic and refractory metals to structural metals, particularly those used in aerospace structures. Such applications take advantage of the higher weld-joint efficiencies and reduced distortion and shrinkage possible in electron-beam welding. Table XXIX presents joint-efficiency data for electron-beam welds in several different structural materials.

e. Other typical applications of electron-beam welding include: fabrication of turbocharger components and turbine-wheel-and-shaft assemblies, joining segments to produce large-diameter rings of Type 2219 aluminum, salvaging of expensive finish-machined parts, and hermetically sealing microrelays.

185. THEORY

a. The electron gun is the key to electron-beam welding. The electrons are emitted from a cathode in the gun, shaped into a beam, and accelerated toward the workpiece. This is done by generating the electrons from a heated filament. The electrons are electrostatically shaped into a beam by a negatively charged electrode cup, which surrounds the cathode. The attractions of a positive electrode anode gives them speed and direction. They pass through a small hole in the center of the anode, continuing toward the workpiece in a beam at speeds estimated at 30,000 to 120,000 mi/sec. There is some divergence of the beam as it travels, but this is gradual enough that a beam length of several inches may be used for most applications. The divergence is due to electron repulsion, and requires electromagnetic systems to align and maintain a fine focus of the beam.

b. Four variables control welding heat input:

(1) The beam current, or number of electrons per second striking the workpiece

(2) The speed of the electrons at the moment of impact, as determined by the voltage

(3) The travel speed of the electron gun or work material

(4) The diameter of the electron beam at, or within, the workpiece.

TABLE XXIX. JOINT EFFICIENCY OF ELECTRON-BEAM WELDED SQUARE BUTT JOINTS IN VARIOUS MATERIALS

Material	Thickness, inch	Yield Strength, ksi	Ultimate Strength, ksi	Joint Efficiency, percent
EZ-33A-T5 Mg	5/8	--	17.5	97
5083-H322 Aluminum Alloy	--	35.9	47.9	90
2218T81 Al Alloy	1/2	42.5	50.7	77*
6A1-4V Ti Alloy	5/8	158	168	100
D6-AC (Tempered 900 F 2 hours)	1/2	217	238	98
D6-AC Ausformed 50 percent (Tempered 900 F 2 hours)	1/2	236	247	89
Maraging Steel - 18 percent Ni (Aged 900 F 3 hours)	1/2	249	254	--
Maraging Steel - 18 percent (Aged 875 F 8 hours)	1/2	264	268	--
AM 355 CRT Stainless Steel	0.080	--	194	90

*Test specimen was 0.252-inch-diameter round bar. Full section specimens failed at 82 percent joint efficiency.

The first three, like current, voltage, and travel speed in arc welding, determine the amount of energy available for welding. However, beam spot size has no counterpart in the arc-welding processes. The electron-beam welding process owes much of its capability and flexibility to the fact that the impact area of the heat source on or within the workpiece can be controlled. This controllability and the power available for welding make possible power densities 50 times greater than those available for gas-shielded arc welding.

c. A vacuum is used with electron-beam welding because the electrons have little mass and are easily deflected by collisons with relatively heavy air or gas molecules. Welding is usually done at pressures from 1×10^{-4} to 1×10^{-5} mm Hg. A static vacuum of 1×10^{-4} mm Hg corresponds to an atmospheric purity of 99.99999 percent.

186. EQUIPMENT AND CONTROLS

a. High-Voltage Equipment

(1) High-voltage, electron-beam-welding equipment is usually considered to be that which operates at voltages above 60,000 volts. Present production equipment has a work chamber 36 inches wide by 23 inches deep by 23 inches high, and has an output rating of 25 kw. Larger welding chambers are used for special applications.

(2) The outside of the work chamber has a lead shield for X-ray protection. The chamber is lined with stainless steel, which prevents absorption of large amounts of atmospheric gases when open and is also easy to clean. The inside is lighted with fluorescent lamps, and the work is viewed through a leaded-glass window in the front of the chamber. Any power needed for electrical equipment inside the chamber is provided through a sealed connector. The electron-gun column can be either centered or positioned at one end of the chamber. A worktable is available with both left-to-right and fore-and-aft motion. The table movement can be either manually or motor operated.

(3) The electron gun, electron optics, and optical viewing system compose the electron-optical column. The functioning of the gun has already been described. An electromagnetic lens at the base of the column serves to focus the electron beam. The beam can be focused at various distances below the base

of the column by varying the current to the focusing lens. With a focused beam, spot sizes of less than 0.015 inch in diameter can be obtained at maximum power. At lower powers, 0.005-inch-diameter spot sizes are possible.

(4) Electron-beam welding presents special problems in viewing and fixturing. This is because welding is performed in a sealed chamber with an invisible beam. A microscope viewing system is a part of the electron-optical column and provides a magnified view of the workpiece before, during, and after welding. The viewing system also contains cross hairs for aligning the beam impact point.

(5) A control is available to interrupt or pulse the electron beam. This allows for the selection of a number of pulse frequencies and pulse widths. Beam pulsing is automatic after the variables have been preset.

(6) The electron gun is mounted above the chamber, allowing ample chamber space for holding and manipulating the workpiece. This also allows the use of a vacuum valve in the column that isolates the gun from atmospheric pressure when the chamber is open. This reduces gun contamination and increases filament life; it also allows cleaning of the gun and changing of filaments without venting and reevacuating the chamber.

b. Low-Voltage Equipment

(1) Low-voltage equipment is generally that which operates at less than 60,000 volts. Because of the lower voltage, the electron gun can be located inside the chamber and may be mobile along two axes. The chamber has a plain-steel wall, which is generally an adequate X-ray shield.

(2) Low-voltage electron guns generally operate at a maximum accelerating voltage of either 30 or 60 kv. The capacity of the power supply determines the maximum beam current. The power supply is a three-phase, full-wave, high-voltage transformer and rectifier. It is usually contained in an oil-filled tank. For low-voltage electron-beam-welding machines, the high power-supply capacity ratings are usually 7 to 30 kw. This allows maximum electron-beam currents ranging from 250 to 1000 milliamperes.

(3) The low-voltage electron gun offers some unique features. First, there is only one control parameter. Any electron-beam current less than the maximum can be obtained by a reduction of the accelerating voltage. A second feature is that the electron gun can be made to operate at lower values of current at a given operating voltage by increasing the distance between the anode and the cathode.

187. VACUUM EQUIPMENT

The work chamber is evacuated by a combination of vacuum pumps operated in an automatic sequence. A mechanical displacement-type pump is used to reduce the pressure from atmospheric to a preset value, usually about 1×10^{-2} torr (1 torr is approximately equal to 1 mm Hg). The pumping is then automatically switched to an oil diffusion pump, which reduces the chamber pressure to the required level. Total pump-down time to 1×10^{-4} torr is generally 3 to 5 minutes for smaller systems, and 8 to 15 minutes for larger systems.

188. WORK-HANDLING EQUIPMENT

a. Establishing the proper initial relative positions of the heat source and the weld joint is particularly critical in electron-beam welding because of the very narrow welds. For example, in 1/2-inch-thick AISI Type 302 stainless steel, the weld would be 0.040 inch wide or less. Thus, a mislocation of only 0.020 inch could cause the beam to completely miss the seam. For this reason, a telemicroscope system, mentioned earlier, may be used to position the electron gun.

b. Maintaining the proper position is as important as setting it properly. This is largely a function of proper design and assembly of the welding machine. Accuracy of the motor controls is equally important, since weld geometry in electron-beam welding is dependent on the energy-input rate.

c. Special locating and holding equipment may be designed as required for particular jobs. The size of the work chamber can be designed to conform to the size and shape of the particular parts to be welded. A multiple station, rotary-welding fixture for welding small parts on a semiautomatic basis may also be used.

189. QUALITY ASSURANCE

a. The very narrow and deep geometry of the electron-beam weld joint has been discussed in Paragraph 173a. From a quality-assurance viewpoint, it should be recognized that this is not a result of high or low voltage alone. It depends on many factors, including the total power and the specific power-delivering capabilities of the welding equipment and their effects in combination with welding speed. If narrow welds are to result, the total beam power must be sufficient to permit the use of rapid welding speeds. Also, the beam power density must be great enough to develop and maintain a hole equivalent to the depth of the weld.

b. Although wide electron-beam welds are not usually desirable, this is not always true. A wide beam may allow the removal of interfacial contaminants and result in joints of higher ductility, less porosity, and possiply lower strength. Such joints may be made in a high-voltage system by beam defocussing or by an oscillation of the beam. They may also be produced by the wider beam of low-voltage systems.

c. Many of the applications of electron-beam welding have already been discussed. However, prior to the application of the process on a production basis, mechanical properties and compositions of weld joints should be closely investigated. With mechanical properties, there is no difference from conventional welding. However, the extreme power concentration and the high-vacuum environment of electron-beam welding can cause volatilization effects not common with conventional techniques. Because of this, detailed chemical analyses of weld compositions are suggested when metallurgical properties may be drastically affected by loss of either alloying elements or minor constituents.

d. As with other processes, the quality of the finished weld with electron-beam welding depends to a large extent on the precautions taken prior to welding. Joint preparation is extremely important. All oxides, dirt, grease, oil, or marking ink must be removed from the joints and the area immediately adjacent to them. Weld tooling, which is near the joint, must be equally clean. Localized mechanical cleaning may be accomplished with a garnet cloth or a wire brush. The residue created must then be removed by a thorough washing with a solvent that will not leave a residue itself. This may be naphtha, methyl ethyl ketone, or ethyl acetate. If filler wire is to be used, it must be free from any surface or internal contamination that might affect the quality of weld deposits. Prior to use, the chemical analysis of the wire should be checked to specification requirements.

e. Electron-beam welding usually produces joints with less porosity and with superior metallurgical and mechanical properties compared to other types of fusion welding.

190. SAFE PRACTICES

a. Electron-beam welding presents a safety hazard in the exposure of personnel to both accelerated electrons and to secondary radiation in the form of X-rays or neutrons. X-rays are by far the more common problem. It is not necessary here to go into details of how this radiation is emitted, detected, and measured. However, mention should be made of means of protection.

b. Any mass of material will provide shielding from X-rays. For very low-energy X-rays, air may act as an absorber, but in general, the greater the mass of a material, the greater the shielding it provides. Thus, materials having a high atomic number, such as lead, are usually used. It should also be noted that the intensity of X-rays varies inversely as the square of the distance from the source to the point of interest.

c. As stated earlier, in low-voltage equipment, the steel-wall thicknesses required for a vacuum chamber are generally adequate for X-ray shielding. However, with high-voltage equipment, additional shielding must be provided. The viewing window in this equipment is also a possible source of X-ray leakage, and lead glass may be added over the usual plate glass for shielding. The plate glass should be the inner layer, however, as the lead glass may have gassing effects during vacuum pump-down. The joint between the window and steel casing, or the door and casing, is another possible source of leakage. The rubber gaskets sealing these joints provide little shielding and must be overlapped with an adequate lip of shielding material.

Section II. LASER WELDING

191. DEFINITION

A laser is a device that produces a concentrated, coherent light beam through the manipulation and control of energy exchanges in solid-state transparent media. In laser welding, the concentrated energy of a focused laser beam at or near the point of contact of the two workpieces results in fusion of the two pieces. The amount of metal melted depends upon the intensity of the laser beam and the total energy it transfers. Figure 73 shows a schematic representation of laser welding equipment. Figure 74 shows a comparison of ordinary light and laser light.

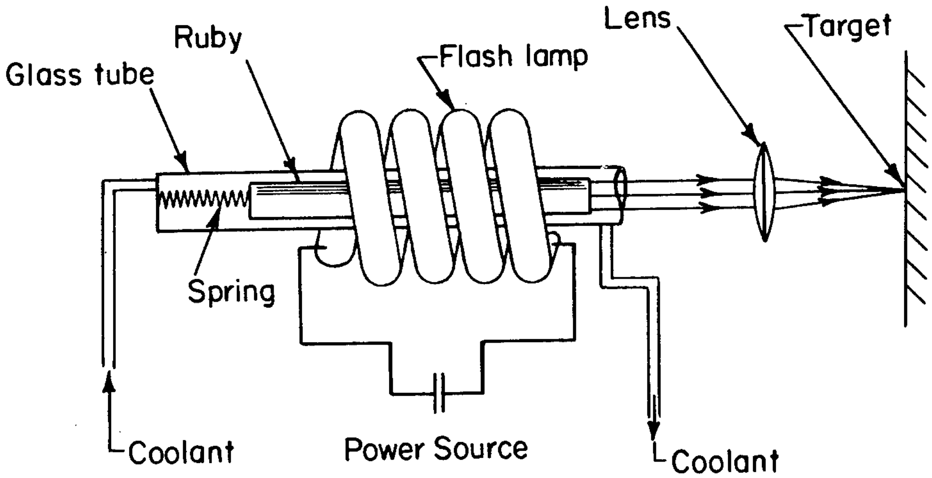


FIGURE 73. LASER WELDING EQUIPMENT

FIGURE 74. COMPARISON OF ORDINARY LIGHT AND LASER LIGHT

192. IMPORTANCE AND USES

a. The laser beam is attractive for fusion welding for several reasons:

(1) The laser beam, when optically focused, has a very high intensity, rivaled only by the electron beam.

(2) Energy from the laser is in the form of light and can be used in any transparent environment, including air, vacuum, inert gas, and certain liquids, and through transparent windows. The source does not need to be near the workpiece.

(3) Mechanical contact with the workpiece is not necessary, and the workpiece does not have to be a conductor of electricity.

(4) The laser beam is almost perfectly collimated and monochromatic, so that very simple optical systems can be used to bend, direct, and focus the laser beam with high precision.

b. With present technology, the power for welding can be obtained only with lasers that deliver energy in discrete pulses rather than in a continuous beam. This is due primarily to thermal factors. For every unit of light energy delivered to the workpiece, 100 to 1000 units of heat energy are released within the laser cavity itself. Because of the problem of dissipating this heat, the repetition rate with which pulses can be produced is limited. Only at very low levels of intensity and average power can a continuous beam be maintained. At the levels of intensity required for welding, the pulse durations are so short and the time between pulses so long, that the metal melted by a pulse of energy completely solidifies and cools before another pulse can be delivered.

c. Welding speed and the thickness of a material that can be welded with a laser are limited by how fast heat can be conducted into the metal, not by the available total power. Two pieces of 0.025-inch-thick aluminum could be spot welded using a pulse duration of about 3 milliseconds and with less than 10 joules total energy. This is possible with present devices. If the material were steel, 30 milliseconds and something less than 30 joules per pulse would be required. The longer time required for the steel is due to its lower heat diffusivity, which means that more time is required for heat to penetrate the steel. This pulse duration is not available with present equipment, and presents a serious obstacle to laser welding.

d. Some of the metals that have been laser welded, in both similar and dissimilar metal joints, include: copper, nickel, tantalum, stainless steel, aluminum, tungsten, titanium, and columbium. Welds are generally wire-to-wire, sheet-to-sheet, or wire-to-sheet.

(1) Wire-to-wire welds have been made using butt joints, lap joints, and T-joints. The lap joint is generally preferred, although sound welds can be made using butt and T-joints. The lap joint can be made with simple fixturing, and the laser energy is delivered to the precise spot where the weld nugget is needed. Fully penetrated wire weld joints

have strength equal to the parent metal in the annealed condition. The electrical resistance of the joint is negligible.

(2) Seam welds between sheets can be made with overlapping spot welds. The required laser energy output for welding a given thickness of sheet is generally about 50 percent higher than for the same-diameter wire. Although good welds can be made with the laser using present equipment and its slow repetition rate, a weld just a few feet long would take about an hour. Thus, seam welds are presently limited to very short lengths.

e. Laser welding must be looked upon as an unusual welding tool for unusual applications. It will probably not find a place with routine welding jobs. The area in which it shows most promise is the electronics industry, with its trend toward miniaturization. Welding is preferred to soldering for these applications, but conventional techniques often cannot meet the requirements. Laser welding, on the other hand, with its precise focusing, can reach barely accessible joints while avoiding any thermal damage to components.

f. Certain guidelines are available to help determine when laser welding might be used. Laser welding can generally be used for welding pieces less than 0.020 inch thick. Any application should take advantage of at least one of the following features: (1) low heat input compared to other processes, (2) high-power intensity, which can help to make difficult welds, (3) a light beam as a heat source, which allows welding of any joint where a direct line of sight is available, although direct contact may not be possible, and (4) the ability to perform precision welding with a well-defined focused spot.

193. THEORY

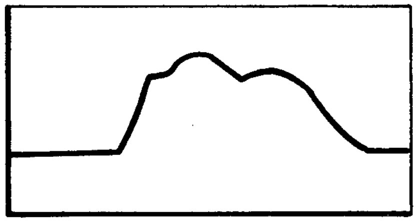
Solid-state lasers are based on transparent single crystals or vitreous substances that contain small concentrations of transition elements. The transition-element atoms can be excited to various energy levels upon exposure to intense optical radiation. For example, the material most commonly used in solid-laser devices of sufficient energy output for welding is the ruby, which consists of aluminum oxide with a small concentration of chromium oxide in solution. The ruby is exposed to the very high-intensity optical-radiation output of one or more xenon flash lamps. During exposure, some of the chromium atoms are excited to a high energy level. After the radiation flash, these chromium atoms immediately drop to an intermediate

energy level with the evolution of heat, and eventually drop back to the ground state, with the evolution of a discrete quantity of radiation in the red part of the optical spectrum. When a large number of chromium atoms in the crystal are in the process of being elevated to high-energy levels and returning to their nominal level, the red-light output is self-amplified, because a chromium atom at the intermediate energy level drops back to ground state much more rapidly when stimulated by the red-light output of its neighbors. The effect is accentuated by arranging the geometries of the crystal such that the red light which is produced reflects back and forth along the length of the crystal. Some of this red light escapes from the end of the crystal in the form of an almost perfectly monochromatic and nondivergent red beam of light. This beam can be manipulated with simple optical systems to accomplish local heating.

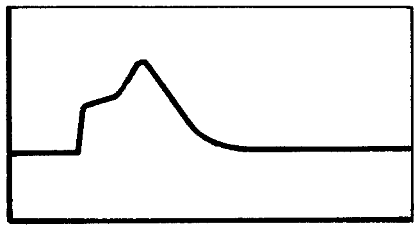
194. QUALITY ASSURANCE

a. The efficiency with which the heat of a laser beam is utilized for melting metal is very high, approaching 100 percent. However, if the required energy is delivered too rapidly, there will not be time for heat to be conducted to the interior of the metal. As a result, there will be superheating rapid evaporation, and expulsion of metal from the surface of the materials being joined, but no deep-penetrating fusion zone. The thickness of material that can be welded with present laser equipment is limited by the maximum pulse times that can be accommodated. With most common metals, surface boiling and expulsion of metal will develop at power intensities around 10^5 to 10^6 watts/cm^2. This limitation would be typical for pulse durations in the range of 3 to 7 milliseconds, and would be somewhat lower with longer pulse durations. When this intensity limit is exceeded, partial vaporization and melting of the metal result. This vaporization is rapid enough to create a force which expels metal leaving a hole, rather than a weld bead. Generally, the penetration that can be achieved increases with the square root of the available pulse time, and with the square root of the thermal diffusivity of the material being worked.

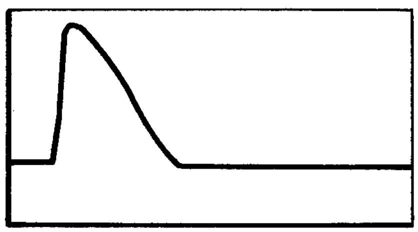
b. The way in which pulsed-heat delivery to a metal surface accomplishes melting or expulsion depends on how the intensity varies with time during the pulse. Almost any desired distribution of intensity can be achieved with the pulse-forming networks governing the power input to the flashlamps. Various pulse forms are illustrated in the oscillograms shown in Figure 75. Generally, if maximum melting and minimum expulsion are to be achieved, the intensity should be high at the beginning of the pulse and decrease with time during the pulse.



a. 3- Millisecond pulse



b. 1.5 Millisecond pulse



c. 1.5 - Millisecond pulse

FIGURE 75. TYPICAL ENERGY-TIME DISTRIBUTIONS

c. Since most metals are good reflectors, one problem that may be encountered in laser welding is loss of energy by radiation. There are two ways to overcome this. One is by darkening or roughening the metal surface to reduce its reflectivity. Another is to arrange the surfaces to be joined so that welding is done in an aperture or crevice. This acts as an absorber and actually allows the reflectivity of metal to be used to advantage. If, for example, two wires are being joined by the laser process, there will be a natural crevice between them, whether they are perpendicular or parallel to one another. Absorption within the crevice is almost perfectly efficient, but at points near the junction, as much as 90 percent of the radiation may be reflected. This assures that melting occurs only at the contact point.

d. The effects of various process variations on laser welding results are illustrated in Figures 76, 77, and 78. These show the effects of laser output, distance from optical focal point, and joint-separation distance on joint strength.

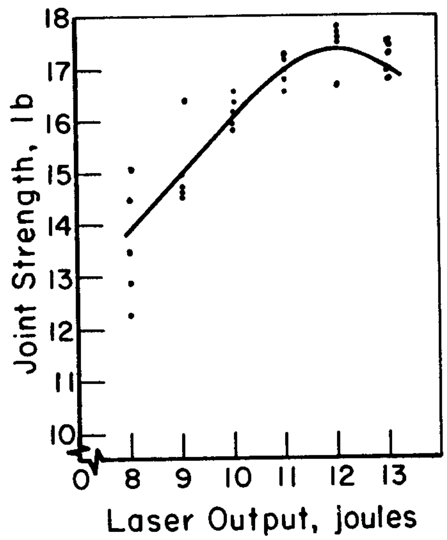


FIGURE 76. EFFECT OF LASER OUTPUT ON JOINT STRENGTH FOR A LAP WELD TO TWO 0.020-IN.-DIAM. NICKEL WIRES

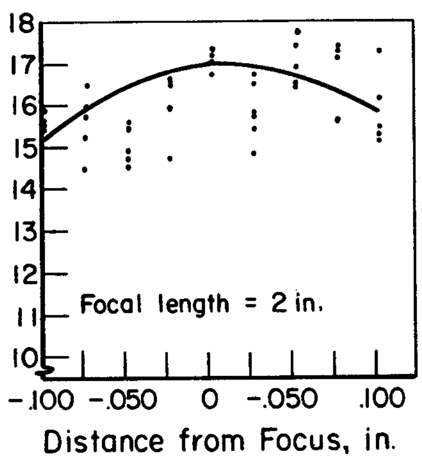


FIGURE 77. EFFECT OF DISTANCE FROM OPTICAL FOCAL POINT ON JOINT STRENGTH FOR A LAP WELD OF TWO 0.020-IN.-DIAM. NICKEL WIRES AT A LASER OUTPUT OF 11 JOULES

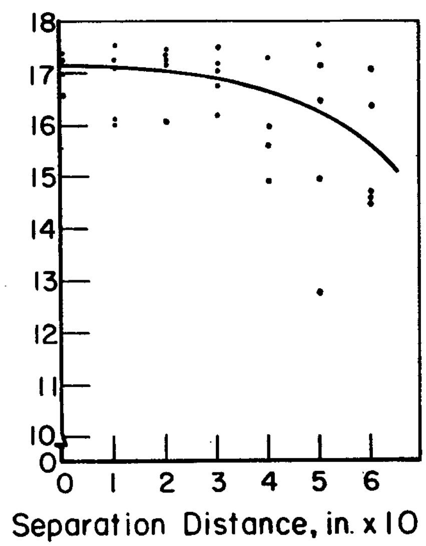


FIGURE 78. EFFECT OF JOINT-SEPARATION DISTANCE ON JOINT STRENGTH FOR A LAP WELD OF TWO 0.020-IN.-DIAM. NICKEL WIRES AT A LASER OUTPUT OF 11 JOULES

195. SAFETY

Laser welding presents special safety problems, as does electron-beam welding. As yet, there has been no problem with X-ray radiation, although this problem could develop with extremely powerful lasers. However, the extreme intensity of the laser beam presents a very real danger of eye damage. Glass that is opaque to the wavelength output of a ruby laser but transparent to white light is available. Protective goggles with this type of glass should be worn by all personnel in an area where lasers are being used. In addition, it is advisable to have protective curtains around laser equipment.

CHAPTER 10

WELDING APPLICATION CRITERIA

Section I. INTRODUCTION

196. GENERAL

The various factors that influence the selection of a welding process for an application will be discussed in this chapter. To properly select a process, it is necessary to be familiar with the various types of joints, joint designs, welding positions, and methods of weld-root finishing, as well as the characteristics of the process and equipment.

197. TYPES OF JOINTS

Five fundamental types of joints are used in welding: butt, tee, corner, lap, and edge, as shown in Figure 79.

198. WELD-JOINT DESIGNS

a. Correct joint design is a vital part of any welding procedure. The safety and service life of the welded assembly depend upon the efficiency of the joint. Correct joint design can help to control distortion, reduce shrinkage cracking, facilitate good workmanship, and produce sound welds economically. The selection of a joint type and joint design depends primarily on the geometry of the part and its intended use.

b. The major consideration in joint design is the service for which the product is intended. If the joint will be subjected to corrosion or erosion, care should be taken to provide joints which, when welded, will not contain irregularities, crevices, or other areas that will render the joint susceptible to such forms of attack. The manner in which stress will be applied in service, whether tension, shear, bending, or torsion, must be considered. Certain joint designs are suitable only for stress applied in one direction, while others are suitable for use when applications of stress are varied or unpredictable. Similarly, statically and dynamically loaded joints may require different designs. The joint design should also be the least expensive joint that will perform satisfactorily in service.

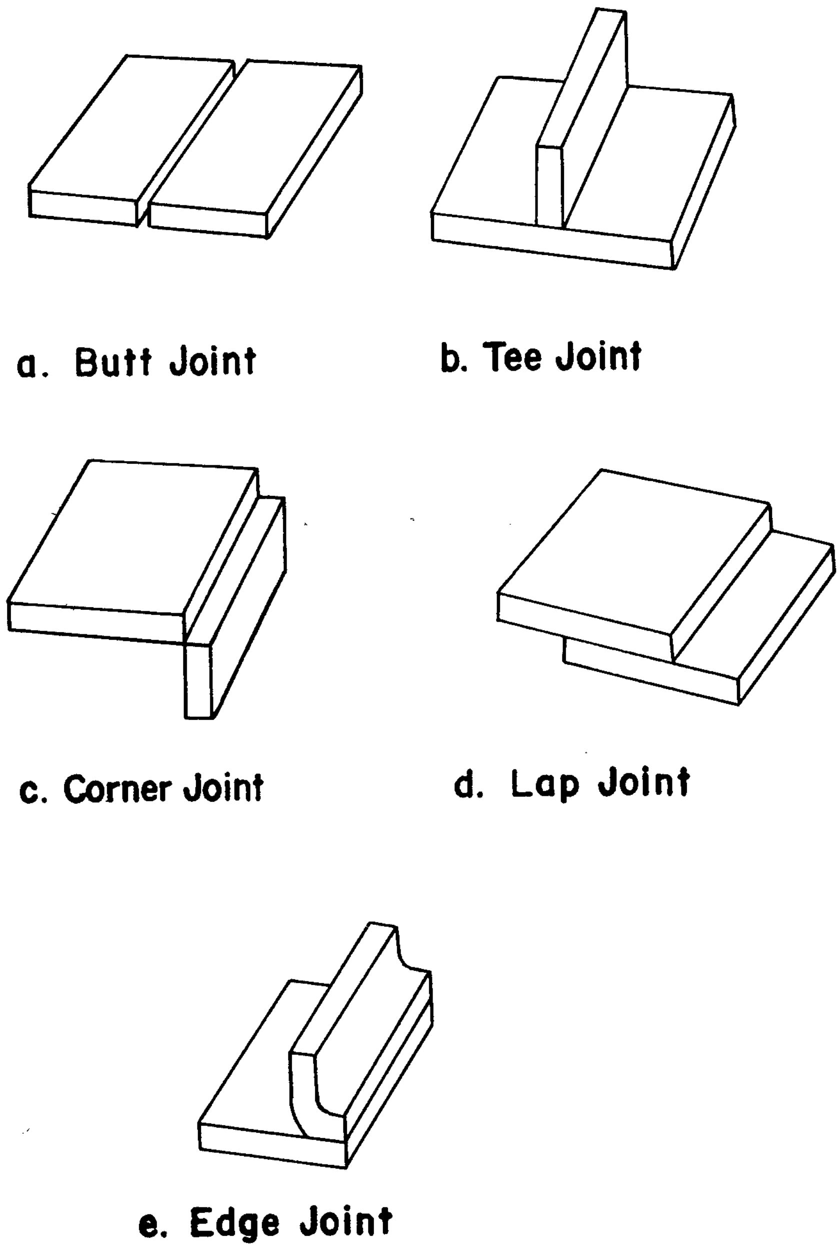


FIGURE 79. FUNDAMENTAL TYPES OF JOINTS

c. Since some joint designs are inherently more difficult to weld and/or inspect than others, quality-control requirements should also be considered when selecting a joint design.

199. TYPES OF JOINT DESIGNS

Each of the five fundamental types of joints may be used with a variety of joint designs. The basic types of joint designs are: (1) groove welds, (2) fillet welds, (3) plug and slot welds, and (4) surfacing welds. Examples of the basic types of joint designs are shown in Figure 80.

200. GROOVE-WELDED JOINTS

a. Groove welds of different types are used in many combinations, the selection of which is influenced by accessibility, economy, and adaptation to the particular design of the structure being fabricated.

b. The selection of the type of groove weld to use is based largely on economy. The square-groove weld is the most economical to use, provided satisfactory soundness and strength can be obtained, since this weld requires no chamfering. Its use is limited by the thickness of the joint. For thicker joints, chamfering of the joint edges is necessary to provide accessibility of welding in order to obtain desired soundness and strength. In the interest of economy, those joint designs should be selected with root openings and groove angles that will require the smallest amount of weld metal and still give sufficient accessibility for sound welds. The selection of root openings and groove angles is greatly influenced also by the materials selected, the location of the joint in the weldment, and the performance required. For example, a 60-degree included angle is generally used for groove joints in steel, while a 75-degree included angle is used for groove joints on nickel and aluminum alloys. Also, smaller angles may be used for the vertical or overhead positions, and special asymmetrical joint preparations are used for the horizontal position. J- and U-groove joints may be used to minimize weld metal required when the savings are sufficient to justify the more difficult and costly chamfering operations. These joints are particularly useful in the welding of heavy thicknesses. One disadvantage of J- and bevel-groove joints is the fact that they are difficult to weld soundly because of the one straight side, which make the entrapment of slag difficult to avoid.

c. The most important criterion of the strength of a groove weld is the degree of joint penetration. Since welded joints are usually designed to be equal in strength to the base metal, groove-welded-joint designs

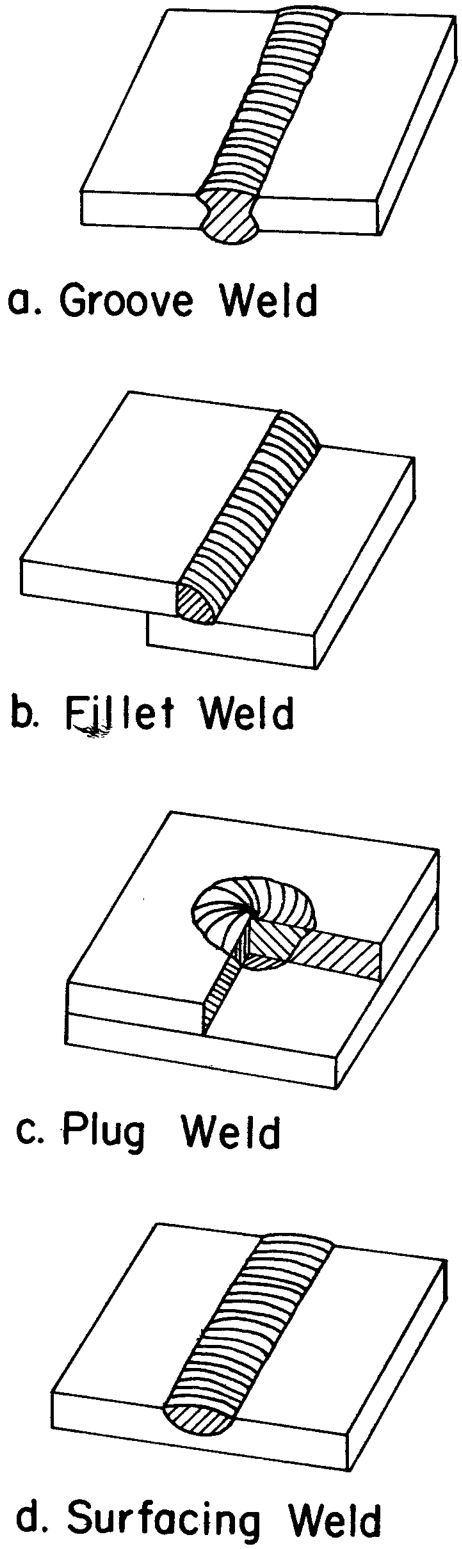


FIGURE 80. FUNDAMENTAL WELD-JOINT DESIGNS

that result in welds extending completely through the members being joined are most commonly used. One of the principles of design is to select joint designs that will result in the desired degree of joint penetration. The recommended details of grooves contained herein have been found to provide a degree of joint penetration consistently predictable when the welding is performed within the limits of the prescribed procedure.

201. PRINCIPAL TYPES OF GROOVE WELDS

The principal types of groove-welded joints are those with a square groove. single-Vee groove, double-Vee groove, single-bevel groove, double-bevel groove, single U groove, double-U groove, single-J groove, and double-J groove.

202. SQUARE-GROOVE JOINTS

a. Square grooves may be used with butt, tee, corner, and edge joints, as shown in Figure 81.

b. The preparation of the square-groove butt joint is relatively simple; it requires only matching of the straight plate edges to be joined with a gap that depends upon plate thickness. Mainly because of the simple method of preparation involved, this type of butt joint is low in cost.

c. If the material being welded is relatively thin, square-groove joints may be welded in a single pass, usually applied from the side which shows in the finished work, resulting in fairly continuous complete penetration. Complete penetration of square-groove joints by welding from both sides can be attained on materials up to 1/8 inch thick without any root opening and on materials up to 1/4 inch thick with adequate root opening.

d. The square-groove tee joint, although not very practical, is like the square-groove butt joint in that no special machining of the plates is required. However, of all types of tee joints, the square-groove tee joint may require the most filler metal and thus can have the highest welding cost.

e. The square-groove corner joint and the square-groove edge joint are also economical from the standpoint of preparation and welding. However, these joints are limited to those applications where the loading is relatively light.

203. SINGLE-VEE GROOVE JOINTS

a. The joints to which single-Vee groove welds apply are the butt and corner joints, as shown in Figure 82.

b. Single-Vee groove joints are economical from the standpoint of welding required, when depth of chamfering is between 1/4 and 3/4 inch. In general, the single-Vee groove joints are suitable for most loading conditions and are used with plate thicknesses considerably greater than the square-groove joints, but their use on thinner sections is not unusual. Preparation of edges obviously costs more than for square-groove joints. At the same time, more filler metal is used to complete the joint.

204. DOUBLE-VEE GROOVE JOINT

a. The double-Vee groove is applicable only to butt joints, as shown in Figure 83.

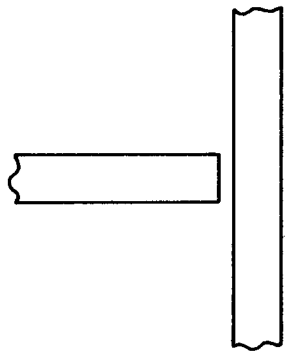
b. With incomplete joint penetration, this type of weld becomes economical when depth of chamfering on each side does not exceed 3/4 inch. With complete joint penetration, the double-Vee groove weld can be employed to advantage for intermediate thicknesses of plates up to 1-1/2 inch. In general, then, the double-Vee groove is used for plates of greater thicknesses than the single-Vee groove. As a matter of fact, for a given groove angle, the double-Vee groove requires approximately only half as much filler metal as the single-Vee groove for plates of the same thickness, but the cost of preparing the edges is higher.

205. SINGLE-BEVEL GROOVE JOINTS

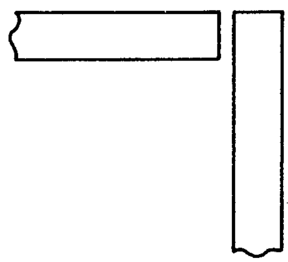
a. Single-bevel groove joints can be used for the butt, tee, and corner joints, as shown in Figure 84.

b. Single-bevel groove joints welded from one side, without complete joint penetration, are applicable when chamfering does not exceed 3/4 inch. If complete joint penetration is attained, this joint may be used for thicknesses between 1/4 and 3/4 inch. The single-bevel groove joints, welded from one side, with backing strip and complete penetration are preferred when welding must be done from one side only. Also, they are economical for thicknesses up to 3/4 inch with regard to amount of filler metal required.

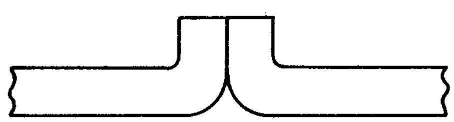
a. Butt



b. Tee



c. Corner



d. Edge

FIGURE 81. SQUARE-GROOVE JOINTS

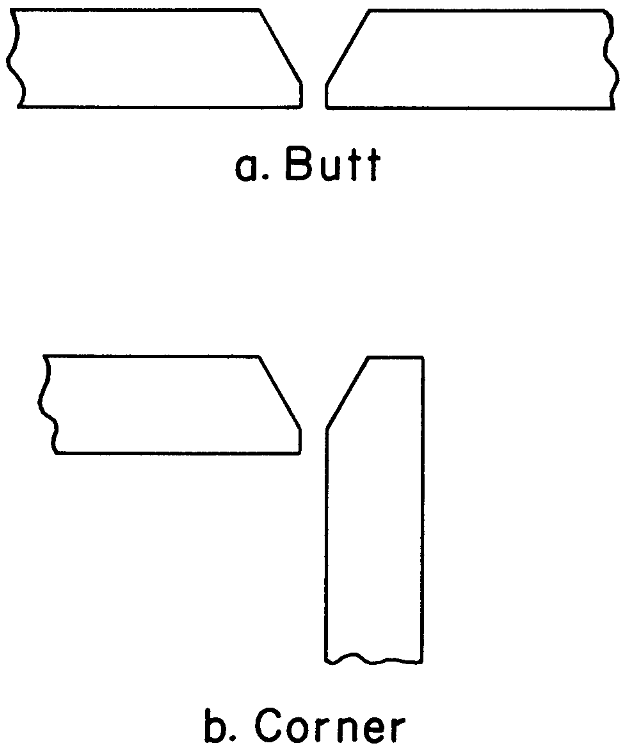


FIGURE 82. SINGLE-VEE GROOVE JOINTS

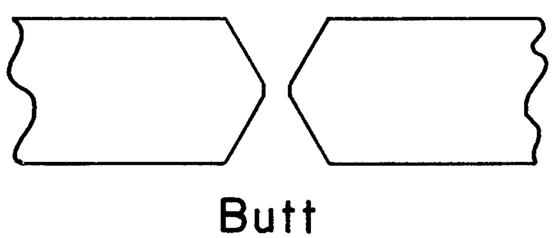


FIGURE 83. DOUBLE-VEE GROOVE JOINT

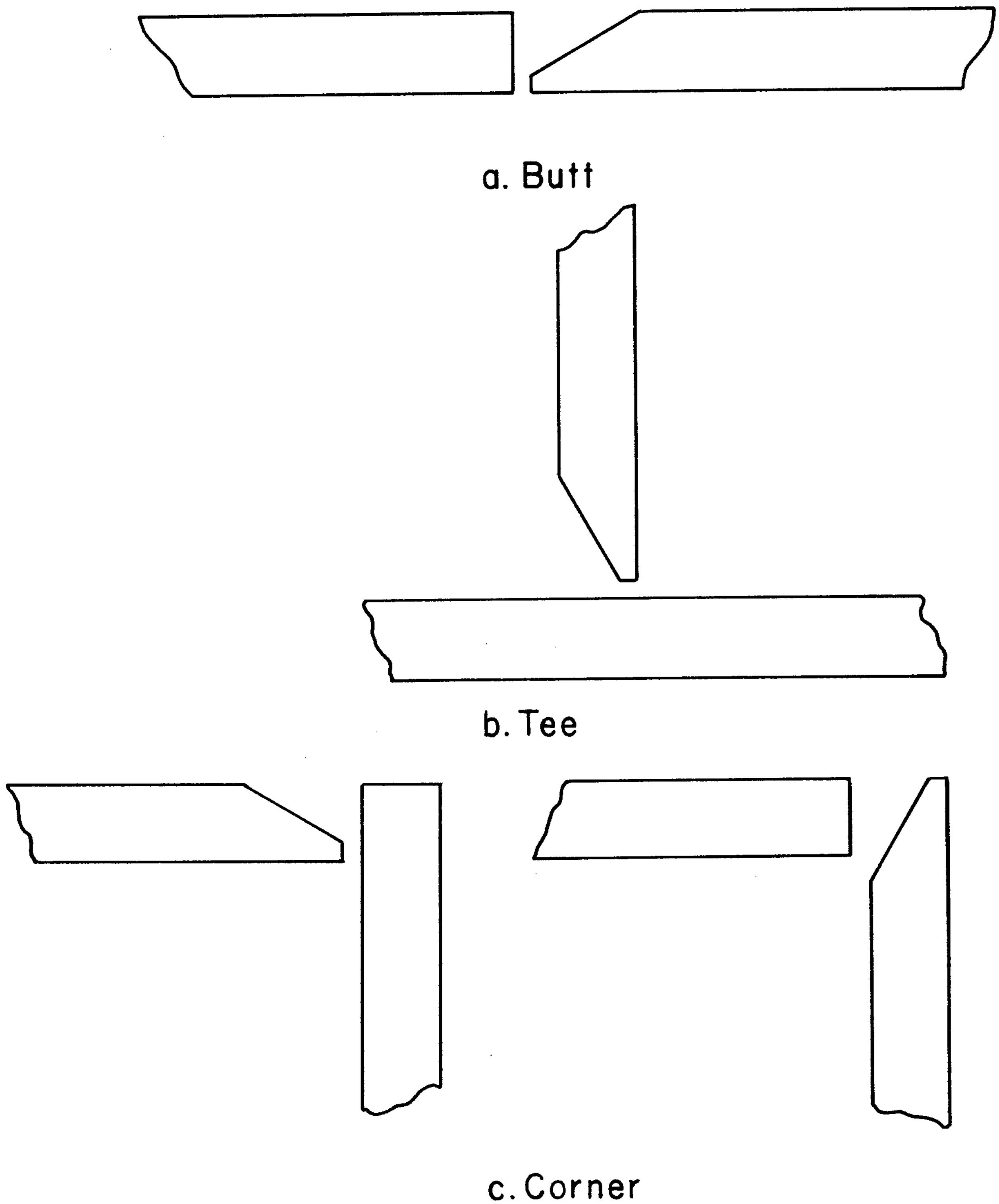


FIGURE 84. SINGLE-BEVEL GROOVE JOINTS

c. When welded from both sides, with complete penetration, single-bevel groove joints may be used economically for plate thickness up to 3/4 inch. Where full strength is required, this joint is recommended in preference to the same type of joint welded from one side only.

d. The narrow included angle of the bevel-groove joint makes it one of the least desirable types of joint. Also, the perpendicular face on one side of the joint can make it difficult to obtain a sound weld, depending on welding position.

206. DOUBLE-BEVEL GROOVE JOINTS

a. The butt, tee, and corner joints can be prepared with double-bevel grooves, as shown in Figure 85.

b. If penetration is not complete, these joints may be used economically when the depth of chamfering on each side does not exceed 3/4 inch. With complete penetration, they may be used economically with thicknesses as great as 1-1/2 inch. These joints do not require an excessive amount of filler metal; as a matter of fact, they require less filler metal than single-bevel groove joints. However, preparation of edges is more costly.

c. The double-bevel groove has the same access problems as the single-bevel groove.

207. SINGLE-U GROOVE JOINTS

a. The single-U groove joints apply to the butt and corner joints as shown in Figure 86.

b. A single-U groove is, perhaps, the most easily welded type of groove because of its rounded bottom, and it is applied to good advantage when the thickness of the work exceeds 3/4 inch. It requires less filler metal than the single- or double-Vee groove, but the cost of machining the edges is greater. It is used for work of the highest quality and is suitable for all usual loading conditions. In general, single-U groove joints are employed to minimize filler metal when the savings are sufficient to justify the more difficult and costly chamfering operations.

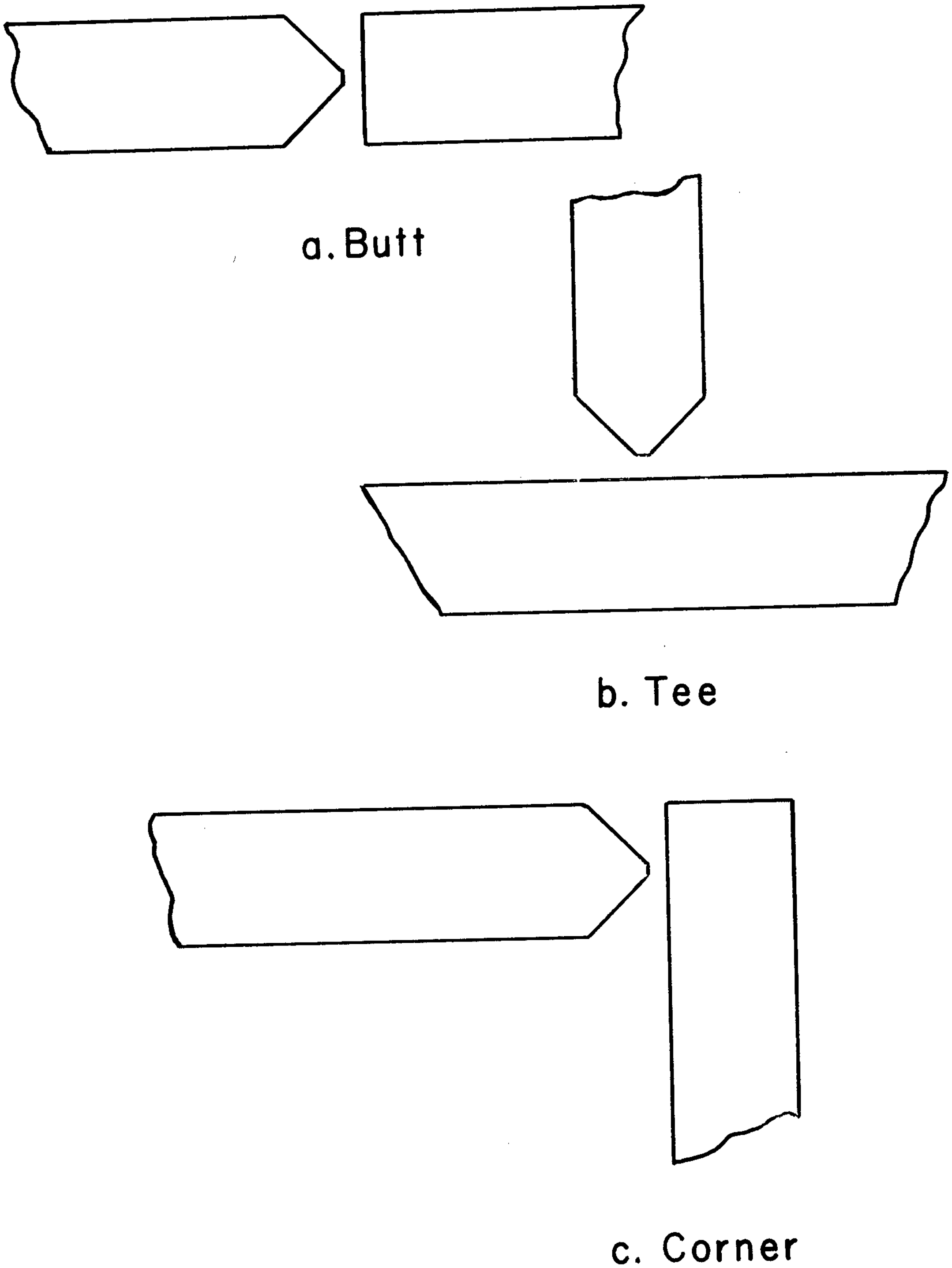


FIGURE 85. DOUBLE-BEVEL GROOVE JOINTS

208. DOUBLE-U GROOVE JOINTS

a. The only joint with which the double-U groove weld can be used is the butt joint, as shown in Figure 87.

b. If the weld does not completely penetrate the joint, the double-U groove joint should be used only when the depth of chamfering on each side exceeds 3/4 inch. With complete joint penetration, the double-U groove joint is very economical when thickness of base metal exceeds 1-1/2 inches. Like the single-U groove, the double-U groove can be easily welded. It requires less weld metal than the other groove joints, but the preparation of the edges is more expensive than bevel or vee grooves.

209. SINGLE-J GROOVE JOINTS

a. The single-J groove may be used with butt, tee, and corner joints, as shown in Figure 88.

b. The single-J groove joint is somewhat more costly to machine than the single-bevel type, but it requires less filler metal. It is applicable particularly when thickness of work exceeds 3/4 inch. The perpendicular side of the J-groove may make it difficult to obtain a second weld, depending on position.

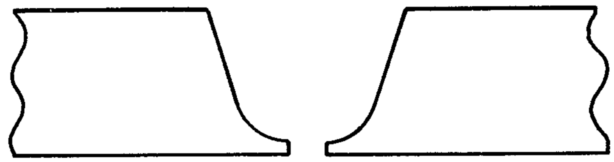
210. DOUBLE-J GROOVE JOINTS

a. Butt, tee, and corner joints may be designed with double-J grooves when advantageous (Figure 89).

b. Double-J groove joints are capable of withstanding severe loads of all types in heavy plates, 1-1/2 inches or heavier, where welding can be done from both sides. A double-J groove costs more to machine, but requires less filler metal than a single-J groove. J-grooves are more expensive to prepare than Vee or bevel grooves.

211. FILLET WELDED JOINTS

a. In certain designs, fillet welds may be used in preference to groove welds because of the greater overall economy realized. Groove welds usually require less filler metal than fillet welds, but the edges for the fillet-welded joints are very simple to prepare and to fit up.



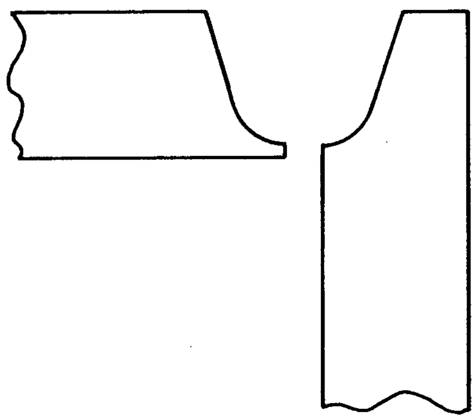


FIGURE 86. TYPES OF SINGLE-U GROOVE JOINTS

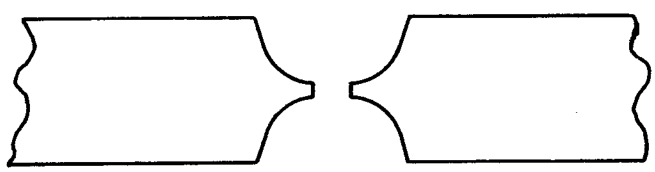


FIGURE 87. DOUBLE-U GROOVE JOINT

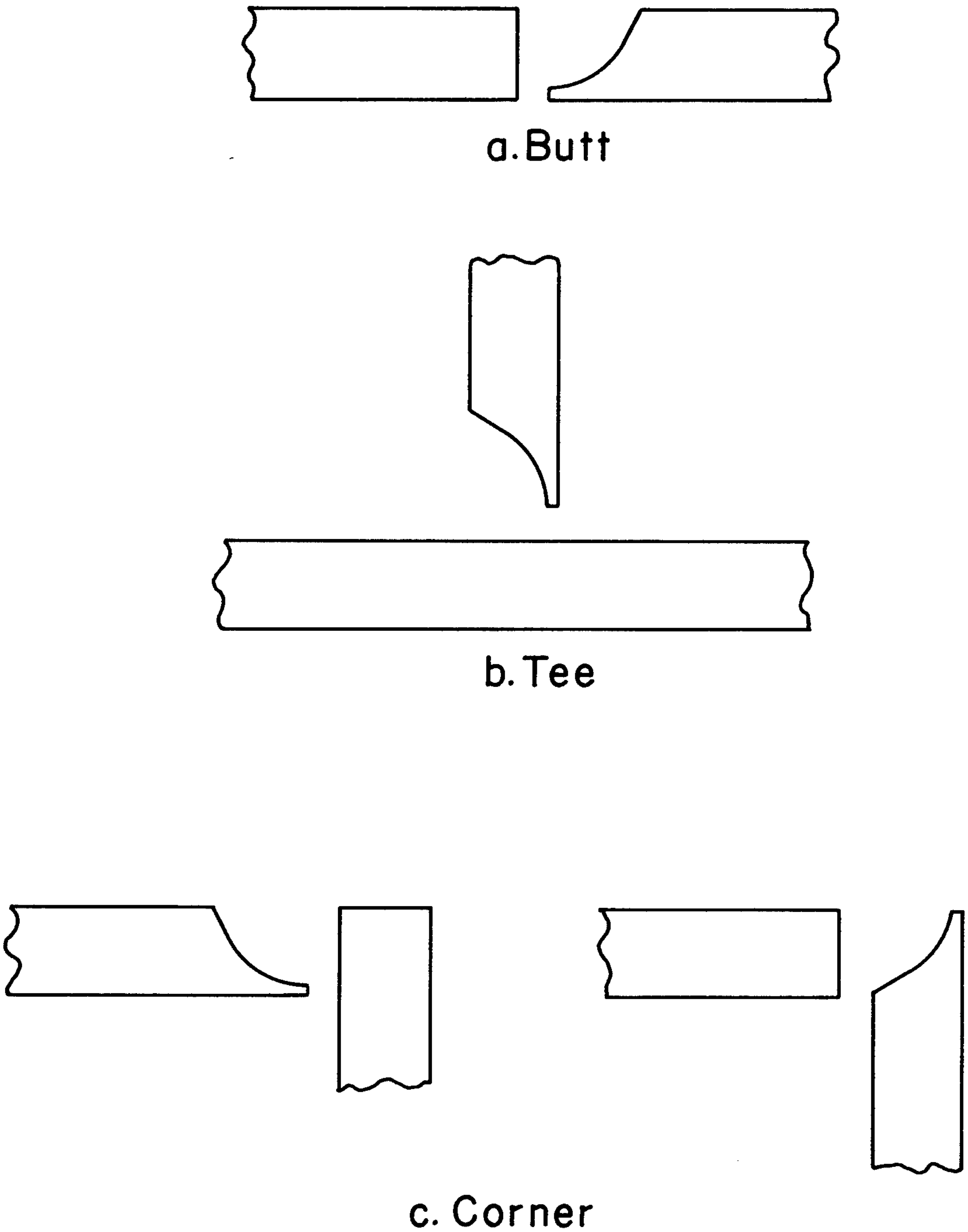


FIGURE 88. SINGLE-J GROOVE JOINTS

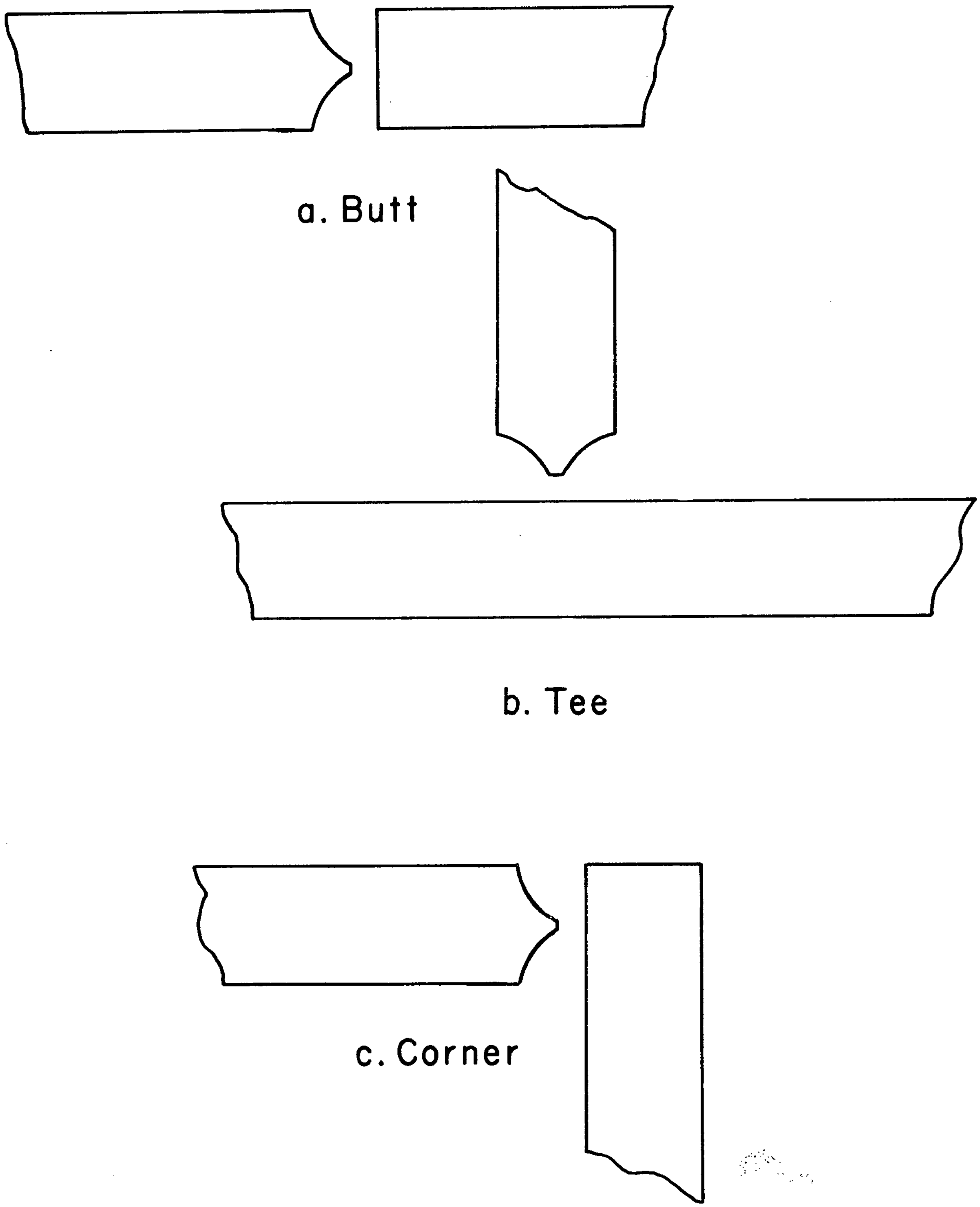


FIGURE 89. DOUBLE-J GROOVE JOINTS

b. In general, transverse fillet welds are stronger than welds parallel to lines of stress.

212. SINGLE-FILLET-WELDED JOINTS

a. The single-fillet-welded joints are the lap, tee, and corner joints (See Figure 90).

b. The strength of these joints depends upon the size of fillet. If loading is not severe, these joints are suitable for welding plates of thicknesses up to 1/2 inch; however, if fatigue or impact loads are applied to the welded structure, or if tension due to bending would be concentrated at the root of the weld, they should not be used.

c. The single-fillet lap joint is frequently used, and has the advantage of requiring practically no edge preparation to fit the edges of the plate. When fatigue or impact loads are encountered, stress distribution should be carefully studied. Where loading is not too severe, the single-fillet lap joint is suitable for welding plate of all thicknesses.

d. The flush corner joint is suitable where loads are not severe, or in welding plate 12 gage and lighter. Although permissible for use on heavier plates, care should be taken that loading is not excessive.

e. The half-open corner joint is suitable for loads where fatigue or impact are not severe. This joint is generally used on plates heavier than 12 gage where the welding can be done from one side only. The "shouldering" effect of this type of joint aids welding by reducing the tendency to burn through the plates at the corner.

213. DOUBLE-FILLET-WELDED JOINTS

a. The lap, tee, and corner joints are welded, for certain applications, with a double fillet (Figure 91).

b. The double-fillet tee and lap joints will develop the full strength of the base metal under static loading, provided that fillet welds of adequate size are used. In the case of the lap joint, an adequate strength in tension is obtained when the lap equals five times the thickness of the thinner member.

c. The double-fillet-welded corner joint is capable of developing full strength for all types of loading. It is suitable for much more severe loading conditions than can be met by the single-fillet-welded joint.

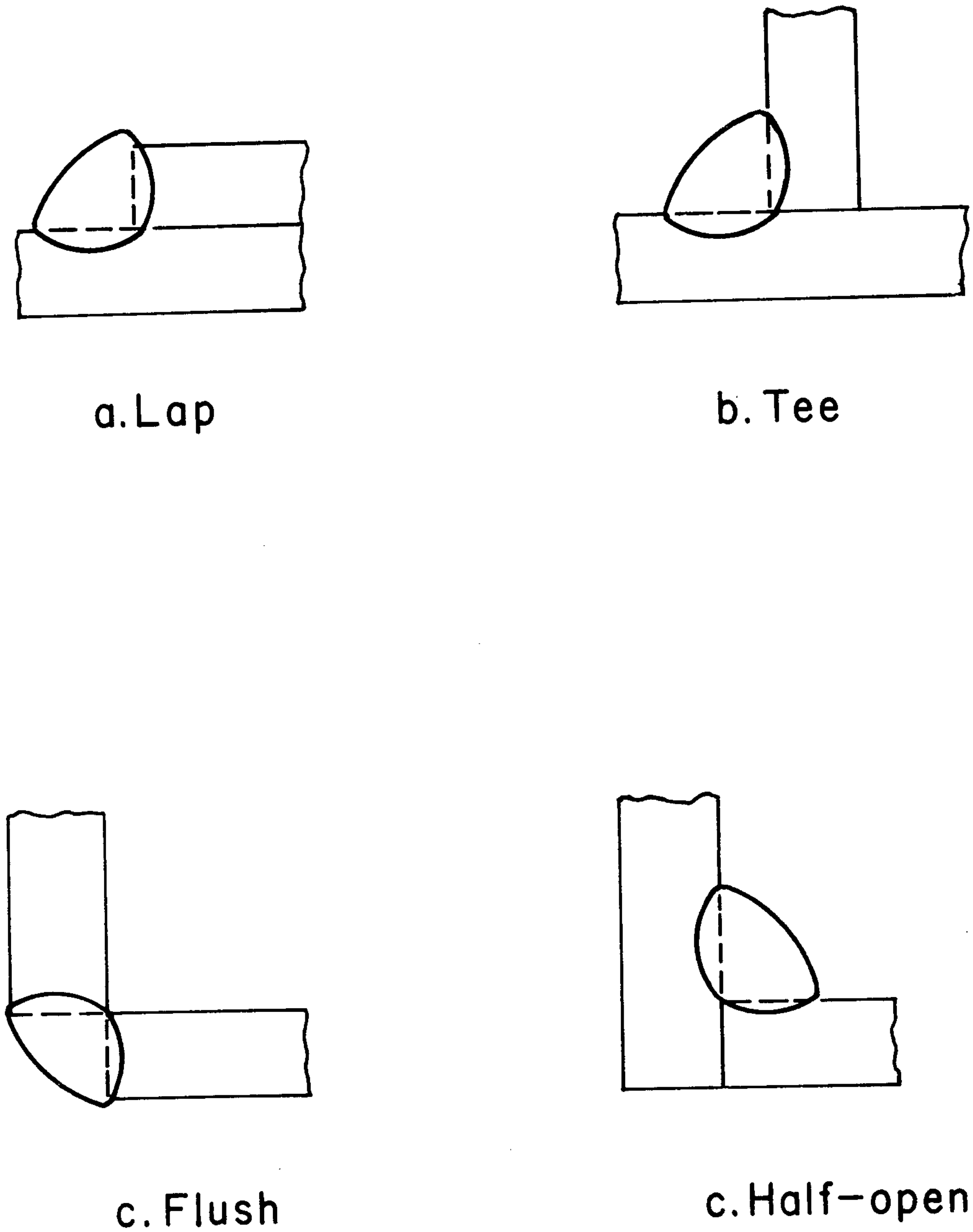


FIGURE 90. SINGLE-FILLET-WELDED JOINTS

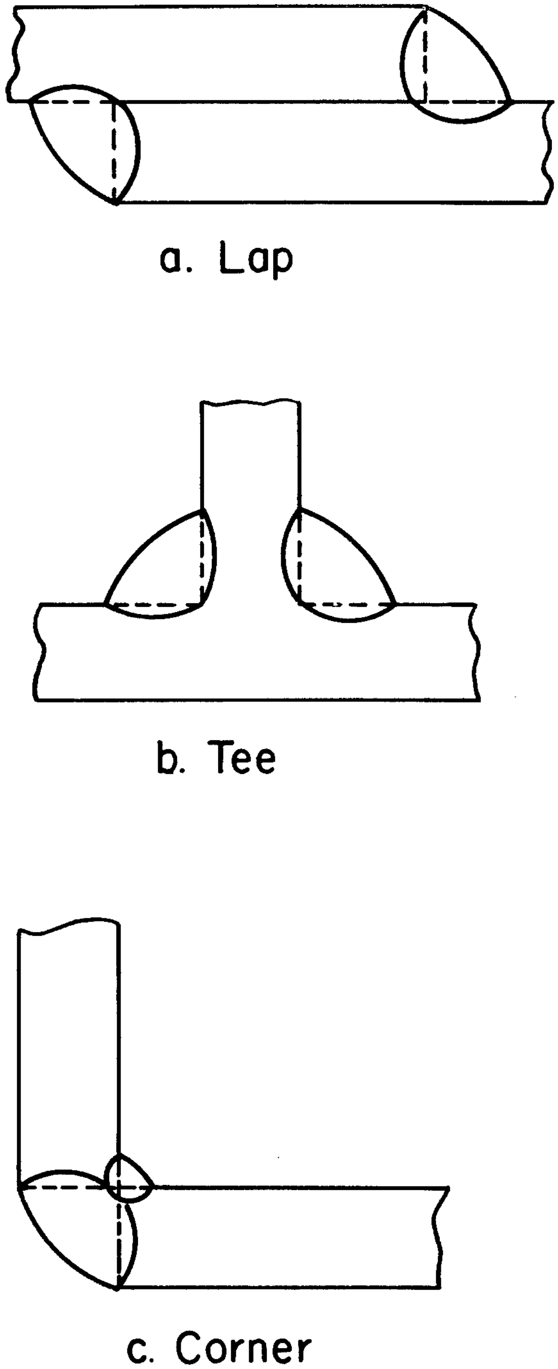


FIGURE 91. DOUBLE-FILLET-WELDED JOINTS

214. COMBINED GROOVE- AND FILLET-WELDED JOINTS

In some applications, fillet welds may be added to groove welds to improve the stress distribution within the joint, as well as to obtain additional strength. This is particularly true for tee and corner joints (Figure 92).

215. FURTHER COMPARISON OF GROOVE AND FILLET JOINTS

a. In comparing the different forms of some of the joints and welds previously described, it may be said that the butt joint is preferable to the single- and double-fillet lap joint (1) when the joint undergoes appreciable tension, bending, and shock or fatigue stresses; (2) when overlapping parts would decrease thermal conductivity where there is a factor; (3) when overlapping surfaces would serve as conductors for liquids and gases, it being thus difficult to obtain tight structures; (4) when there is the possibility of corrosion between the overlapping surfaces; and (5) when a maximum saving in weight is desired.

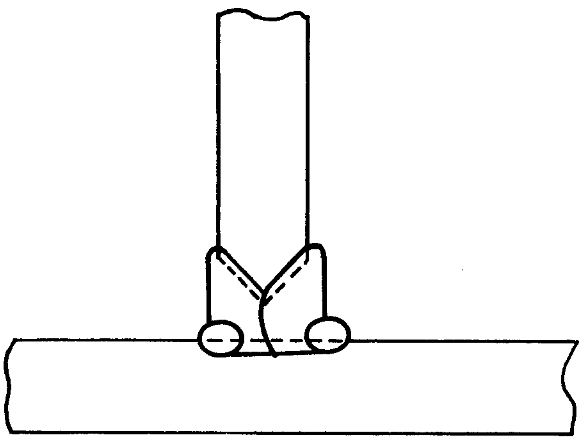
b. Among the main disadvantages of the butt joint as compared with the lap joint are: (1) the greater cost of preparing the joint edges when beveled or grooved; (2) its higher assembly cost in the fabrication of some products; (3) the lack of design flexibility in weld size, for butt welds in most cases are specified as having throat depths that are equal to or greater than the thickness of the thinner part jointed; (4) the greater skill required to make the butt weld instead of the fillet weld; (5) the necessity of using smaller electrodes or filler rods and lower currents or smaller flames for the root layers, except for properly formed U-grooves, which permit use of large electrodes; (6) greater shrinkage; and (7) higher residual stresses.

c. Similar advantages and disadvantages are true for edge and Tee joints with their numerous combinations of fillet, butt, and bead welds. With reference to the edge joint, it must be kept in mind that it is not suitable for high-intensity loading, and careful consideration must be given to the loading conditions, especially impact and fatigue.

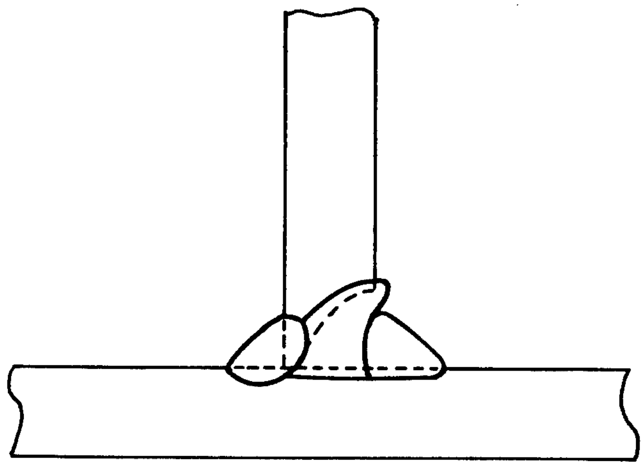
216. PLUG AND SLOT WELDS

a. Plug and slot welds may be used for tee and lap welds, as shown in Figure 93.

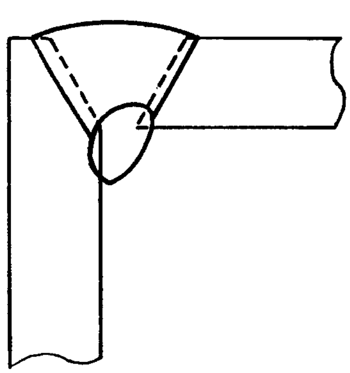
b. Slot welding differs from plug welding in that the weld is made through an elongated slot instead of a hole. Plug and slot welds should not



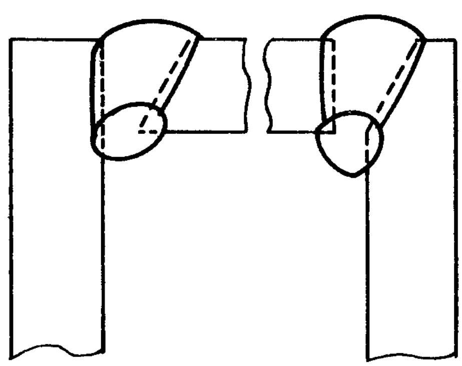
a. Double - Fillet - Welded, Double- Bevel, Tee Joint



b. Double - Fillet - Welded, Single - J, Tee Joint

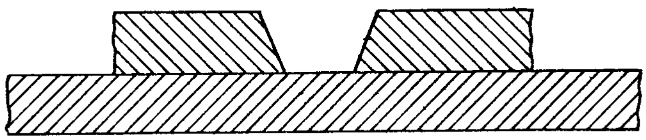


c. Single - Vee Corner Joint, Fillet Welded

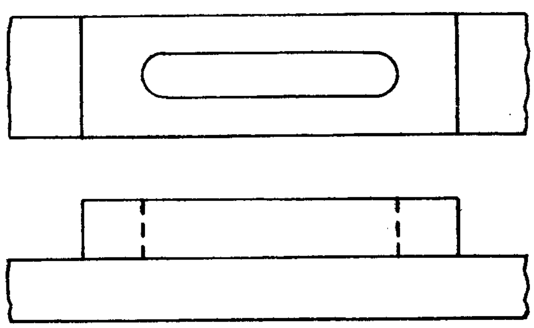


d. Outside, Single - Bevel Corner Joint, Fillet Welded

FIGURE 92. TYPICAL COMBINED GROOVE- AND FILLET-WELDED JOINTS



a. Plug Weld



b. Slot Weld

FIGURE 93. JOINTS FOR PLUG AND SLOT WELDS

be performed by making a fillet weld around the perimeter of the hole or slot. Instead, to develop full joint strength, the hole or slot should be filled in completely with weld metal. Plug and spot welds should not be employed in corrosive environments or for fatigue applications.

217. SURFACING WELDS

Surfacing welds are made by applying one or more weld beads on an unbroken surface to obtain desired properties of dimensions. Common uses of surfacing welds are to correct dimensions on castings or to improve the corrosion or wear resistance of an object. No special joint designs are required for surfacing welds.

218. WELD ROOT FINISHING

a. The weld root is defined as the location at which the bottom of the weld intersects the base-metal surfaces.

b. The condition of the weld root is important because it has a significant influence on the strength and corrosion performance of the weld. Improperly made weld roots may act as stress concentrators under either static or dynamic loading conditions, or may form confined locations where corrosion may begin. For this reason, joints should be designed to facilitate performing welds with proper roots. Careful inspection should be performed after welding to assure that the weld root is satisfactory.

c. The condition of the weld root is of interest primarily for the groove and fillet welds. The quality of the root in plug or slot welds is usually not of interest because these types of welds are not generally used in applications in which the condition of the root can affect the performance of the weld. The subsequent discussion on weld-root finishing will be limited to groove and fillet welds.

d. In properly performed welds, the condition of the root is determined by the manner in which the weld is performed. Welds may be performed from one or both sides of the joint, as either partial or complete penetration welds. Complete penetration welds from one side of the joint may be made with or without a backup.

219. PARTIAL-PENETRATION WELDS

a. Partial-penetration welds may be made from one or both sides using any combination of groove or fillet welds with one of the fundamental

types of joints. Examples of partial-penetration welds are shown in Figure 94.

b. Partial-penetration welds are used because they are simple and economical to perform. They are suitable for statically loaded conditions but may not be satisfactory for fatigue or impact loading because of the stress-concentration effect of the unfused root.

c. Partial-penetration welds may be difficult to inspect nondestructively after welding because the unfused region can cause false indications or indications that mask true defects.

220. FULL-PENETRATION WELDS

Full-penetration welds may also be made from one or both sides using any combination of groove or fillet welds with one of the fundamental types of joints. Examples of full-penetration welds are shown in Figure 95.

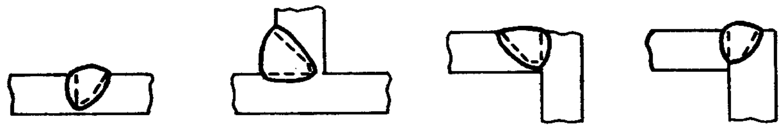
221. SINGLE-GROOVE, FULL-PENETRATION JOINTS WELDED FROM ONE SIDE ONLY

a. Single-groove, full-penetration joints welded from one side only may be accomplished with or without a weld backing.

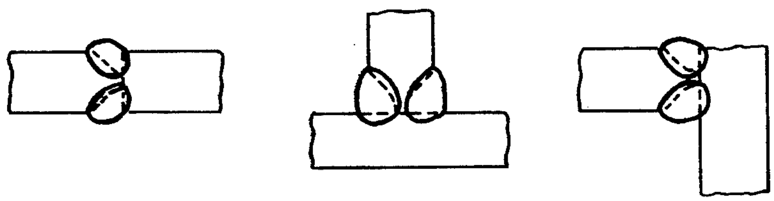
b. When single-groove, full-penetration welds are welded from one side without a backing, it may be difficult to obtain proper fusion and contour at the root for the entire length of the weld. If part of the root remains unfused, or if the contour is not correct, the root of the weld may act as a stress concentrator. Therefore, single-groove joints welded from one side only should not be used when imposed bending can cause concentrated tensile stress at the root of the weld or when the welded structure will be subjected to fatigue or impact loading. Because of the possible deleterious effect of the weld root on weld performance, the root of single-groove, full-penetration joints welded from one side should be carefully inspected after welding to assure that proper fusion and root contour have been obtained.

222. WELD BACKUPS

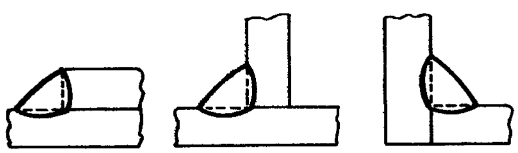
a. Weld backups are sometimes used to facilitate obtaining a proper root in single-groove, full-penetration joints welded from one side. A weld backing eliminates much of the effect of operator technique on root condition for manual and semiautomatic processes by giving him something



a. Welded One Side, incomplete Penetration, Tee Groove

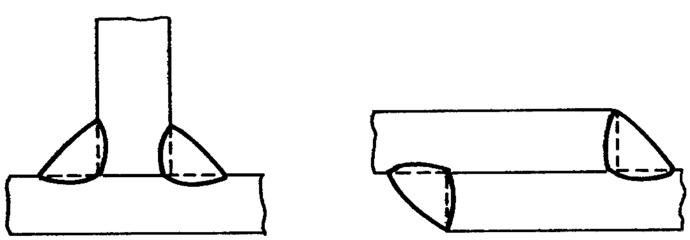


b. Welded Both Sides – Incomplete Penetration, J Groove



Lap Tee Corner

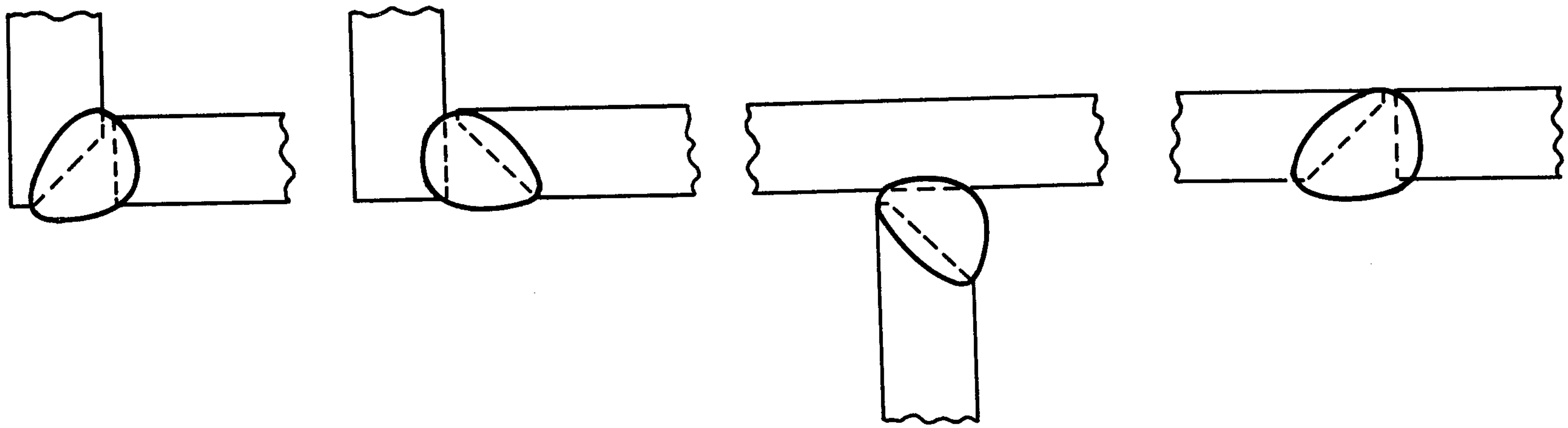
c. Single – Fillet – Welded Joints



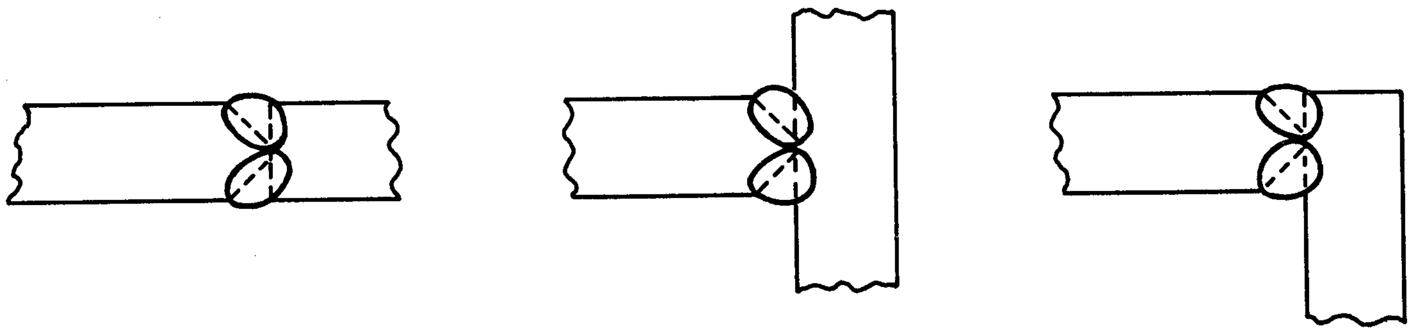
Tee Lap

d. Double – Fillet Welded Joints

FIGURE 94. EXAMPLES OF PARTIAL-PENETRATION WELDS



a. Welded One Side, Complete Penetration



b. Welded Both Sides, Complete Penetration

FIGURE 95. EXAMPLES OF FULL-PENETRATION WELDS

to weld against. Weld backings also permit wider latitude in root-pass welding conditions for fully automatic processes.

b. Two types of weld backing may be used for joining ferrous materials: the backing strip or bar and the consumable-insert backing. Copper backing bars, which may be water cooled, are sometimes used for nonferrous materials. Consumable-insert backings are also used for nonferrous materials.

223. BACKING STRIPS

a. The backing strip or bar is a strip or bar that is placed against the back of the weld. The backing strip can be used for almost any joint type, including girth welds in cylindrical weldments. It can be rolled into a circle for use in girth welds. The backing strip may be used to facilitate the welding of joints with large amounts of mismatch. During the root pass, the backing strip is fused to the weldment. An example of a backing bar is shown in Figure 96a.

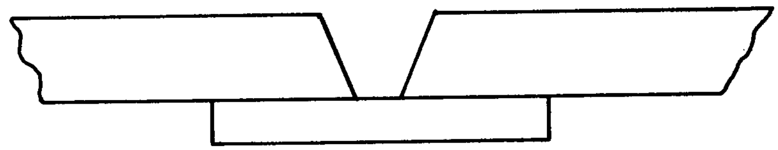
b. Joints welded with backing strips develop full strength under all types of loading. However, if the joint is to be subjected to fatigue loading, the backing strip should be removed, since the notch created by the junction of the weldment, backing, and weld root may act as a stress concentrator and degrade the fatigue performance of the joint. Welds with backing strips should not be subjected to corrosive environments unless the backing strip is removed.

c. Joints with backing strips intact may be difficult to nondestructively inspect because the unfused area between the weldment and the backing strip may cause false indications or indications that mask true defects.

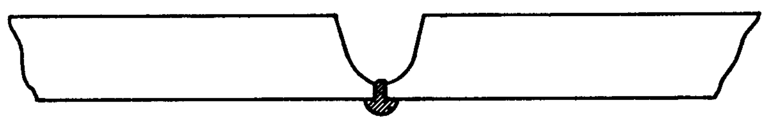
224. CONSUMABLE-INSERT BACKINGS

a. Consumable-insert backings are used primarily for girth seams in pipe. The consumable-insert backing is designed so that it becomes completely fused with the weldment during the root pass. No crevice remains between the backup and the weldment as with backing strips. An example of a consumable-insert backing is shown in Figure 96.

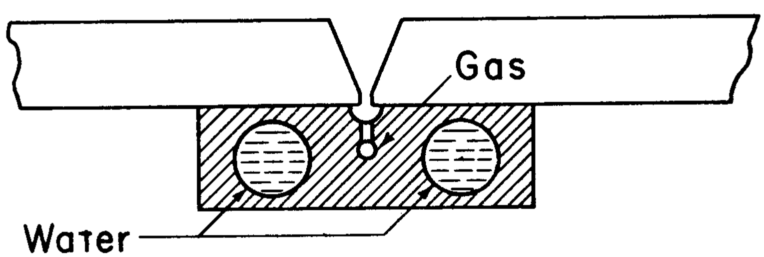
b. Consumable-insert backings are more difficult to fit up than backing strips and require a better operator technique and control of welding conditions to obtain proper fusion. The resulting joint, however,



a. Backing strip



b. Consumable-insert backing



c. Water-cooled copper backing-gas shielding also supplied

FIGURE 96. EXAMPLES OF SINGLE-VEE GROOVE WELD WITH VARIOUS TYPES OF BACKINGS FOR WELDING FROM ONE SIDE

develops full strength under any loading when properly performed, and is suitable for fatigue and corrosion applications in the as-welded condition. Joints made with a consumable-insert backing have better fatigue properties than joints made with backing strips when left in as-welded condition.

c. Joints made with a consumable-insert backing are easier to inspect nondestructively than joints made with backing strips.

225. COPPER-BACKING BARS

Copper-backing bars, which may also be water cooled, are sometimes used for joining nonferrous materials. The water-cooled backing bar is not fused to the weldment as are the backing and consumable-insert backing. Hence, the copper-backing bar does not present the removal problems of the backing strip. The resulting weld root, however, is comparable to that obtained with consumable-insert backings, with its attendant advantages. Copper-backing bars may also contain passages so that an inert gas can be supplied to the back of the joint. A joint with a water-cooled copper backing is shown in Figure 96c.

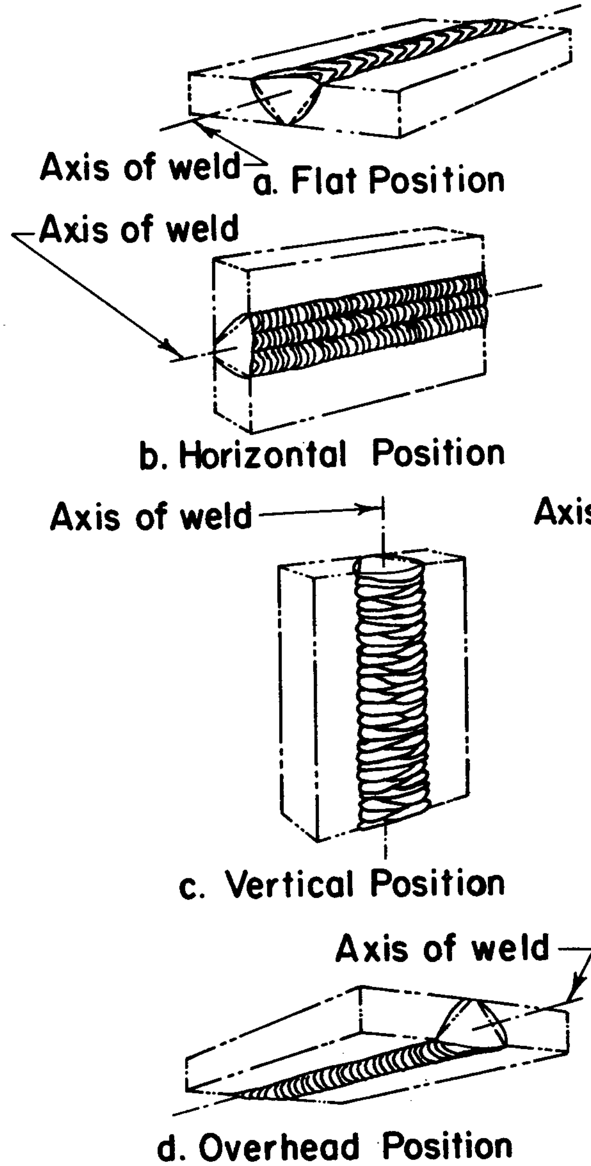
226. SINGLE-GROOVE AND DOUBLE-GROOVE FULL-PENETRATION JOINTS WELDED FROM BOTH SIDES

a. The strength of single-groove, full-penetration joints welded from one side without a backup can be greatly enhanced by removing, or "backchipping", the root and rewelding it. Backchipping may be accomplished by chiseling, grinding, machining, or arc gouging, depending on the weldment material. Single-groove, full-penetration joints welded from both sides are capable of developing the full strength of the base metal, regardless of the type of loading imposed.

b. Double-groove, full-penetration joints welded from both sides always are capable of developing the full strength of the base metal under all loading conditions. Maximum quality is obtained when the root of the weld on the first side is backchipped to sound metal prior to depositing the root pass on the second side.

227. WELDING POSITIONS

a. There are four fundamental welding positions for groove and fillet welds in plate structures, as shown in Figures 97 and 98: flat, vertical, horizontal, and overhead.



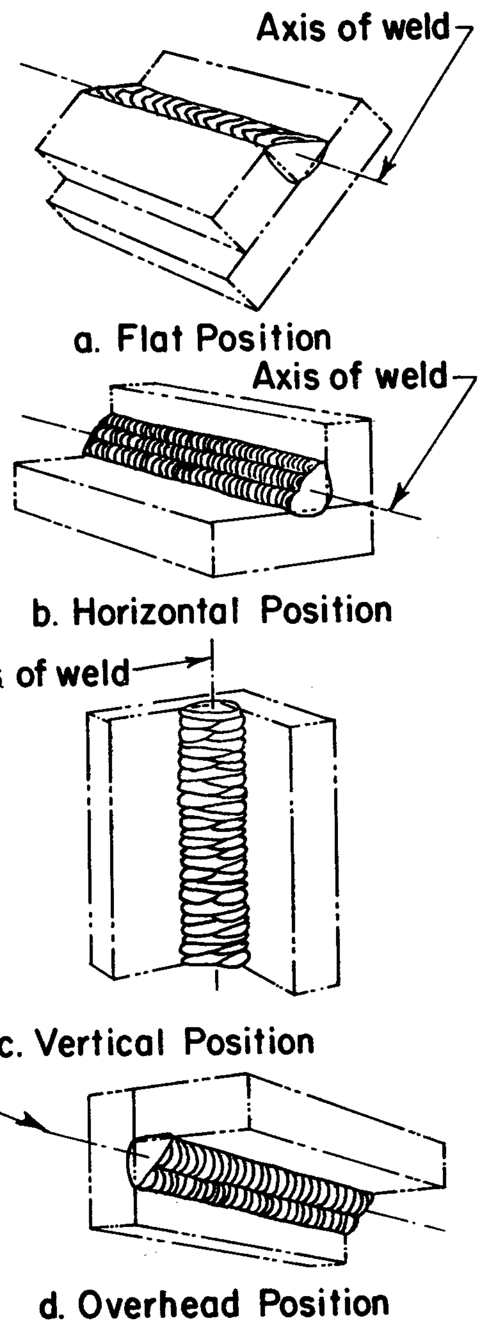


FIGURE 97. POSITIONS OF WELDING FOR GROOVE WELDS

FIGURE 98. POSITIONS OF WELDING FOR FILLET WELDS

b. Since welding in the flat position is generally faster, easier, and less fatiguing than welding in other positions, maximum weld quality is facilitated by designing the structure, or positioning it during welding whenever it is practical to do so, so that only flat position welds are necessary. The order of preference for the other positions or welding is as follows: horizontal fillet welds are preferred to vertical fillet welds, but vertical groove welds are preferred over horizontal groove welds. Overhead welding is as a rule the least desirable of the four positions.

228. WELDING POSITIONS FOR PIPE

a. There are three fundamental positions for welding pipe, as shown in Figure 99: horizontal fixed, horizontal rolled, and vertical.

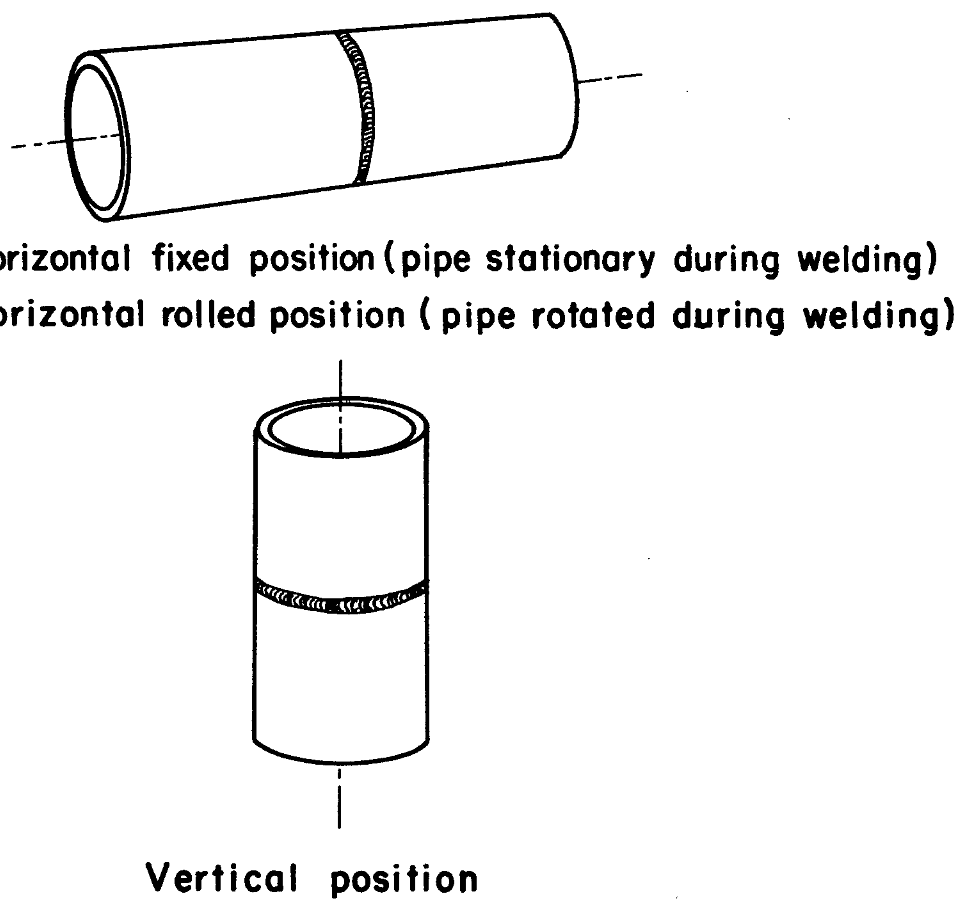


FIGURE 99. POSITIONS OF PIPE DURING WELDING

b. The horizontal-rolled position is the preferred position whenever possible, because all of the welding is done in the flat position. The horizontal-fixed position is the least desirable position because of the overhead welding. When welds made in the horizontal-fixed position are being inspected, special attention should be paid to the joint in the area of transition from the vertical to overhead positions, since this is the most difficult to weld.

229. EFFECT OF POSITION AND BACKING ON JOINT DESIGN

a. The proportions of a joint must be altered whenever the welding position or type of backing is changed. In general, narrower included angles are required for out-of-position groove welds. Horizontal welds generally require special asymmetrical joint designs. The root opening of welds with backing strips is generally larger than for joints with no backing or consummable-insert backings. The recommended joint proportions for the various joint designs, backups, and positions are shown in Figures 100 to 105.

b. Quality control starts with designing joints for the special conditions under which they will be welded. Inspection of joint preparations prior to welding to ascertain that the proper dimensions and tolerances have been maintained will aid in obtaining maximum weld quality.

230. WELDING SYMBOLS

a. Welding symbols provide the means of placing complete welding information on drawings. The symbol may be used for designating welding specifications, procedures, or other supplementary information to be used in making the weld, as well as the size and type of weld. The process, identification of filler metal, whether or not peening or root chipping is required, and finished contour, may also be specified by the symbol.

b. The base elements of the welding symbol and the specific weld symbols are shown in Figure 106. Information on the formulation and reading of welding symbols is also given.

c. Figure 106 also contains symbols for some resistance welds and welding processes because it is a standard American Welding Society chart.

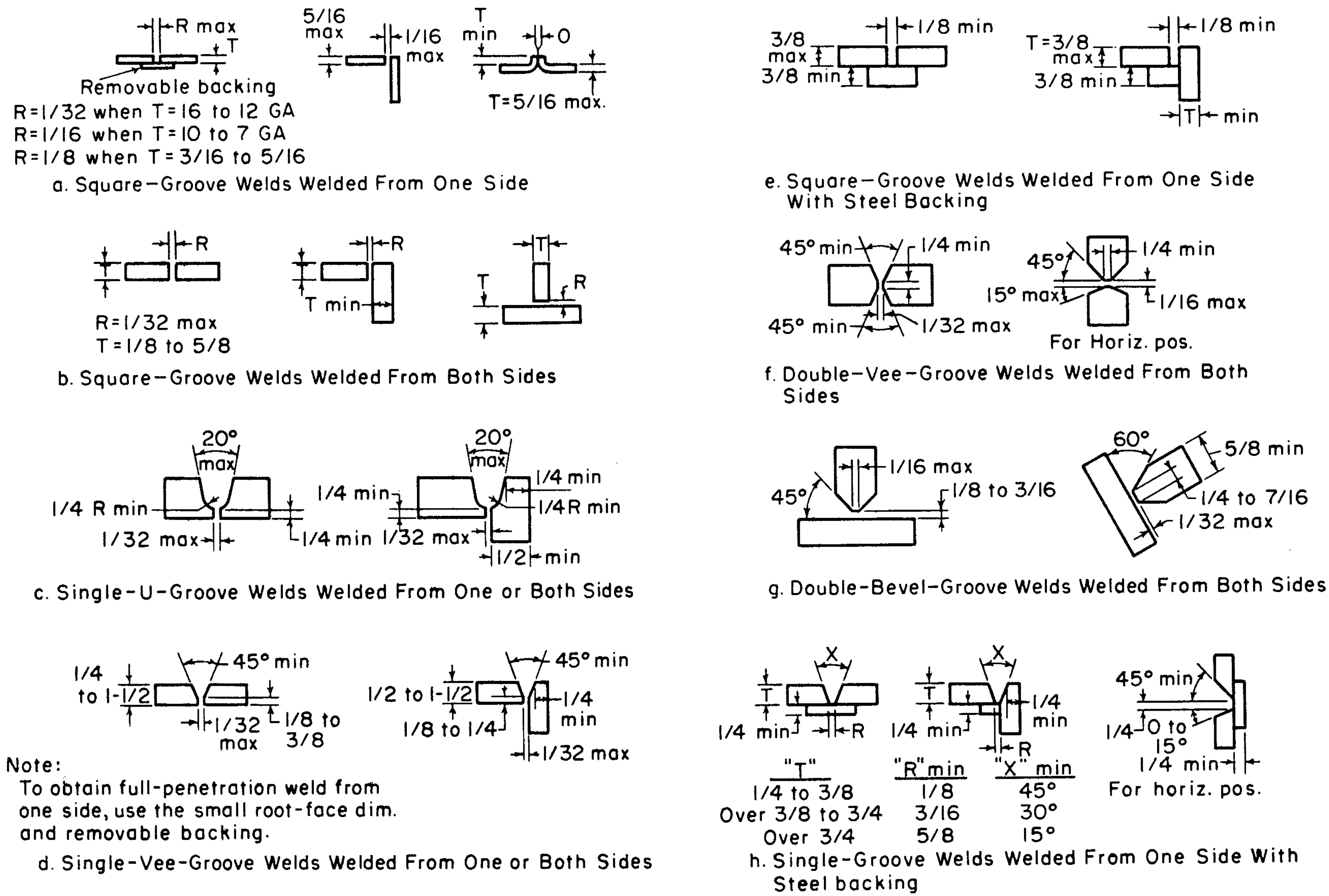


FIGURE 100. RECOMMENDED PROPORTIONS OF GROOVES FOR SUBMERGED-ARC WELDING

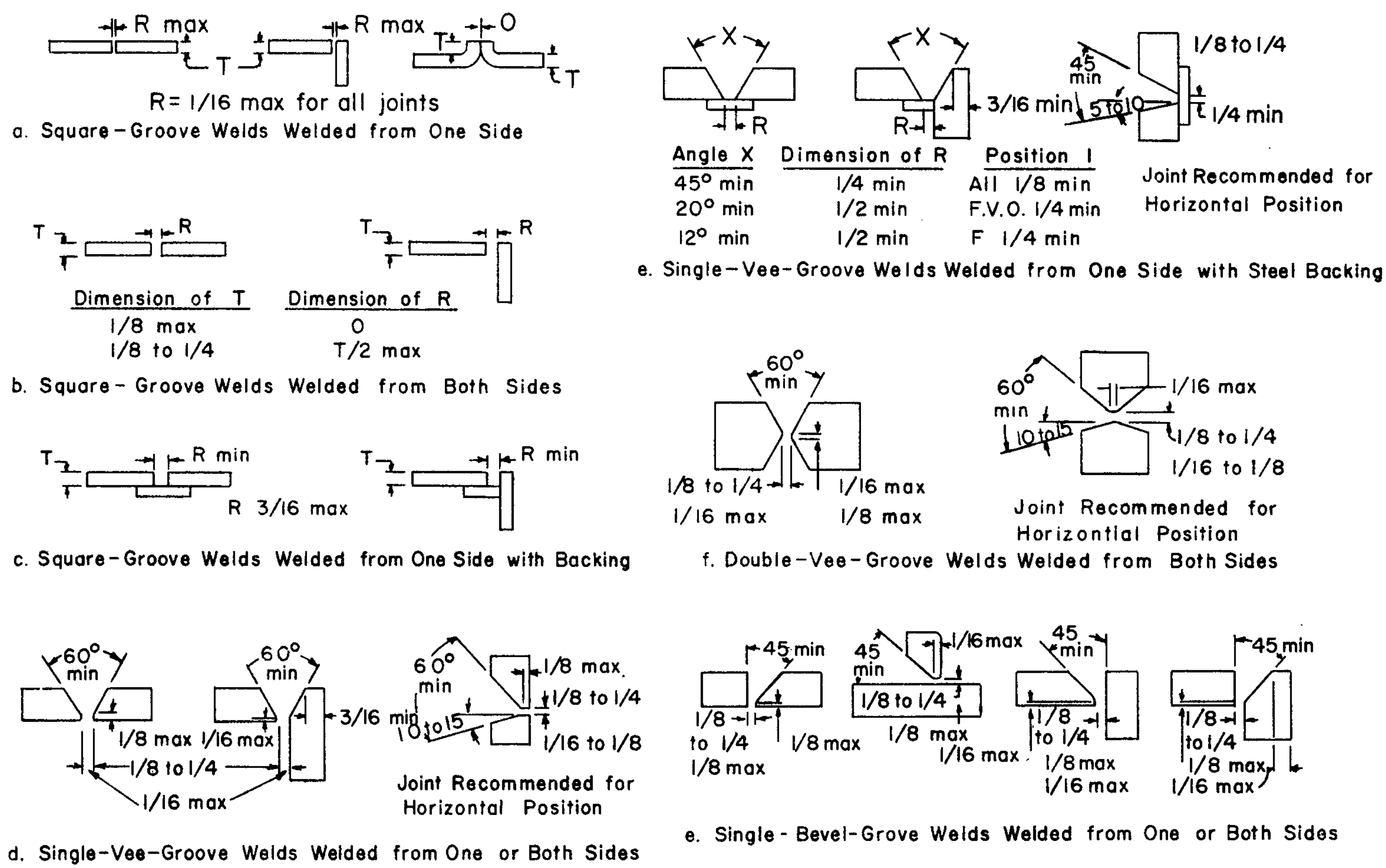


FIGURE 101. RECOMMENDED PROPORTIONS OF GROOVES FOR SHIELDED METAL-ARC, GAS METAL-ARC AND GAS WELDING
(Dimensions marked * are exceptions that apply specifically to designs for gas metal-arc welding.)

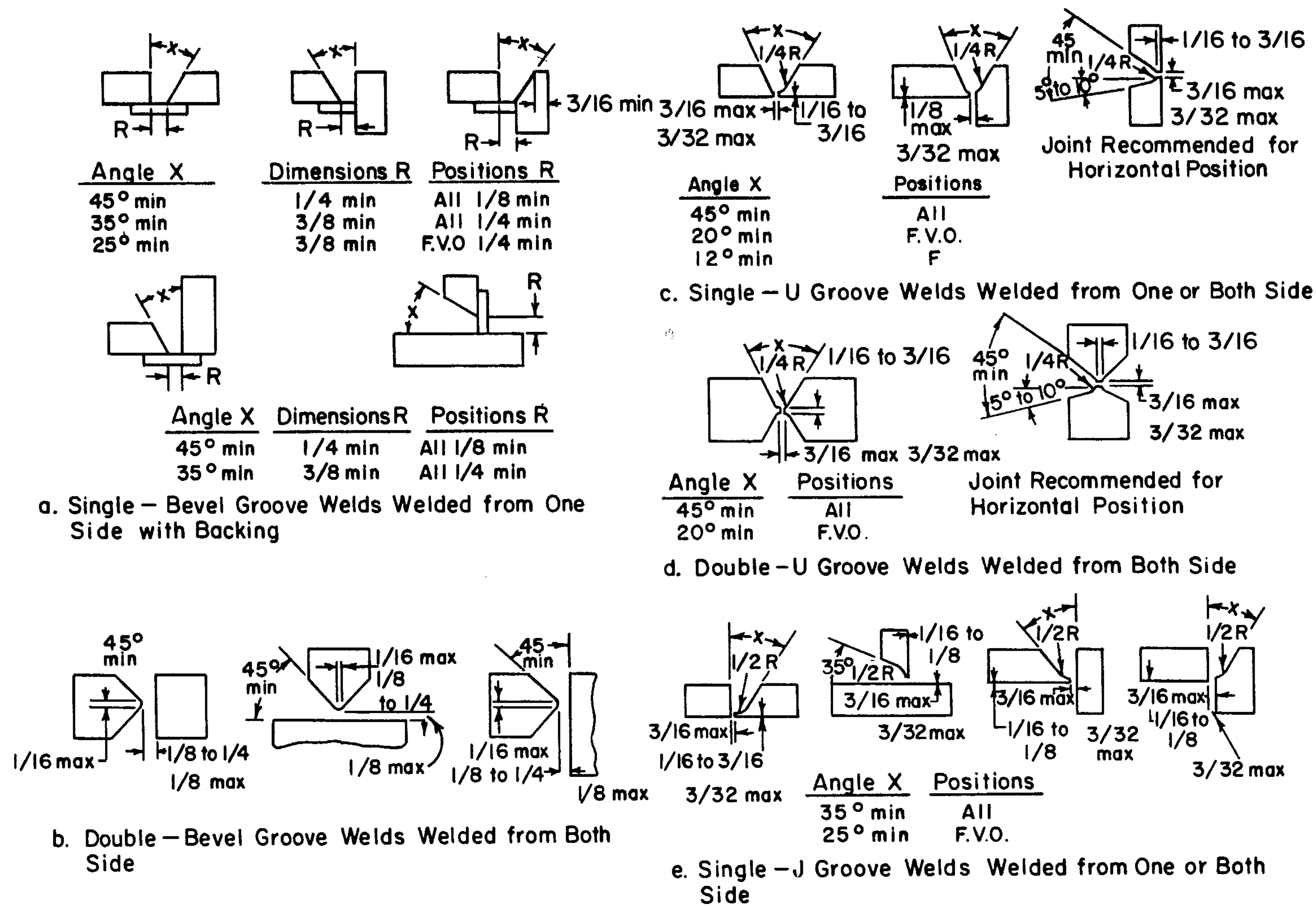


FIGURE 102. RECOMMENDED PROPORTIONS OF GROOVES FOR SHIELDED METAL-ARC, GAS METAL-ARC AND GAS WELDING. (Note: Dimensions marked * are exceptions which apply specifically to designs for gas metal-arc welding.)

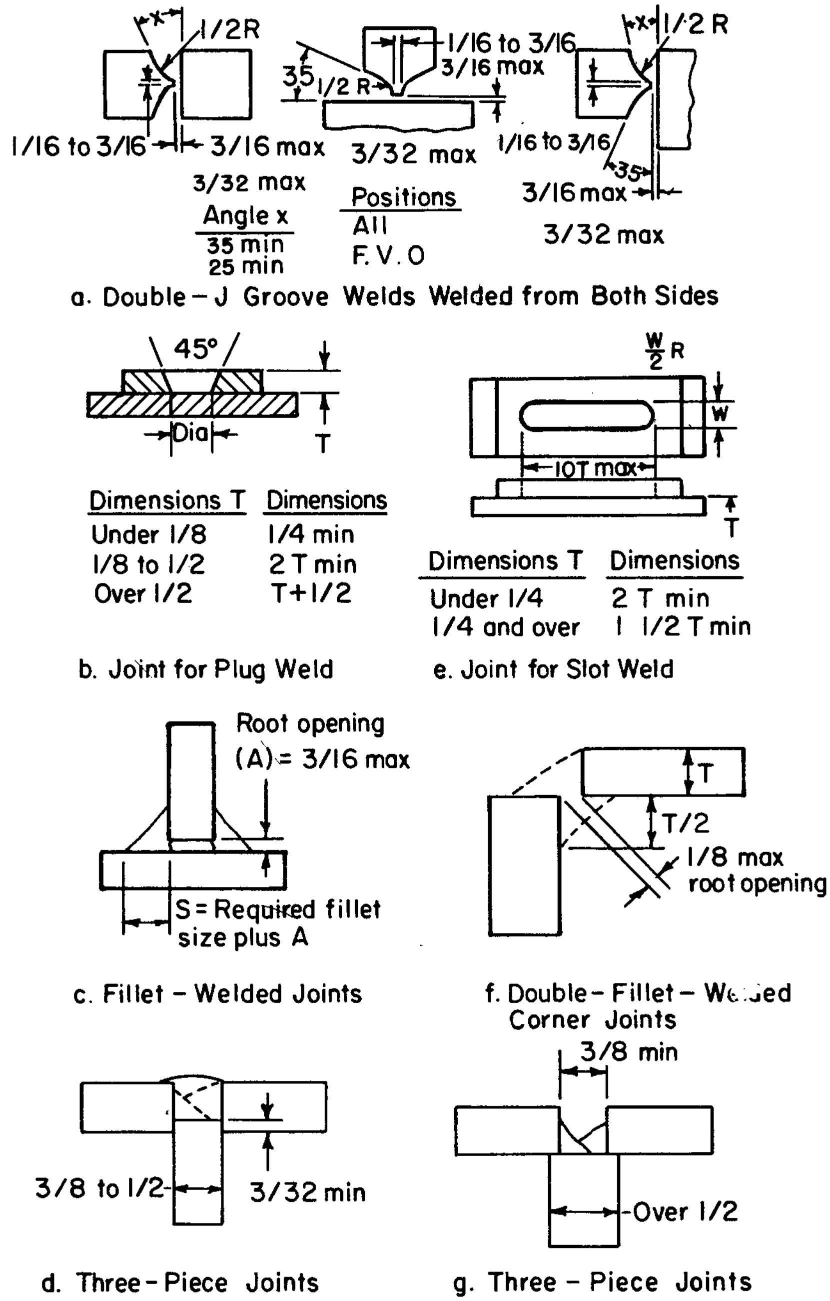
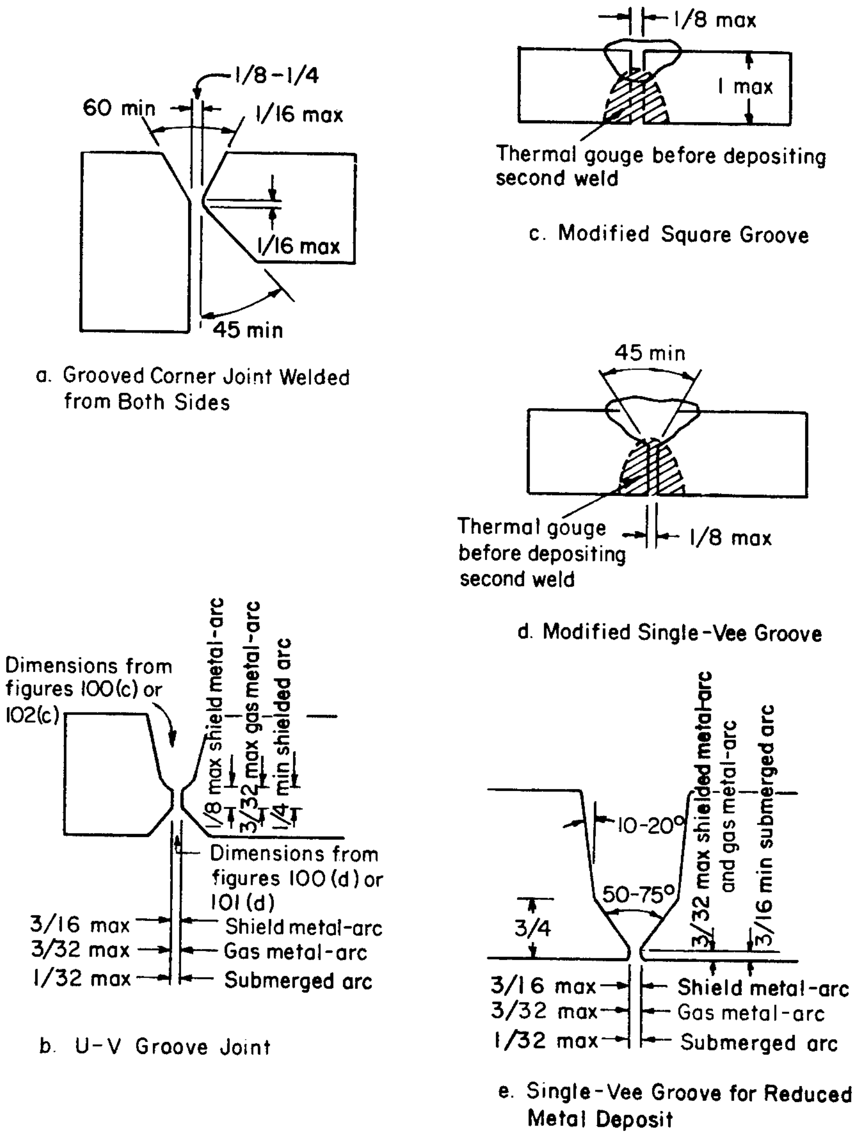


FIGURE 103. RECOMMENDED PROPORTIONS OF GROOVES FOR SHIELDED METAL-ARC, GAS METAL-ARC AND GAS WELDING. (Note: Dimensions marked * are exceptions which apply specifically to gas metal-arc welding.)



a. Grooved Corner Joint Welded from Both Sides

b. U-V Groove Joint

c. Modified Square Groove

d. Modified Single-Vee Groove

e. Single-Vee Groove for Reduced Metal Deposit

FIGURE 104. RECOMMENDED PROPORTIONS OF MIXED GROOVES FOR METAL-ARC WELDING PROCESSES

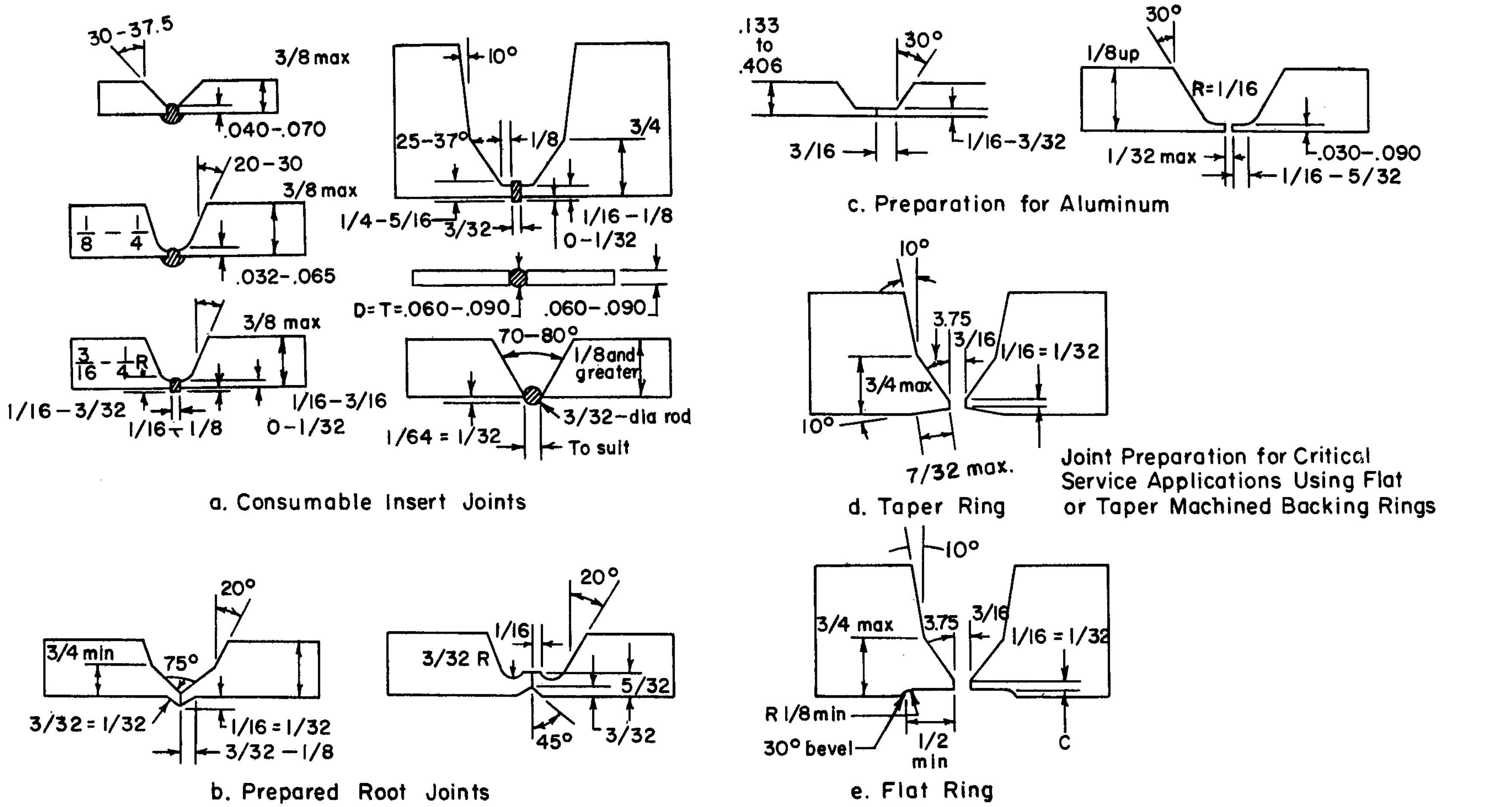


FIGURE 105. RECOMMENDED PROPORTIONS OF GROOVES FOR METAL-ARC WELDING PROCESSES USED TO OBTAIN CONTROLLED AND COMPLETE PENETRATION
(Note: For steel except as noted.)

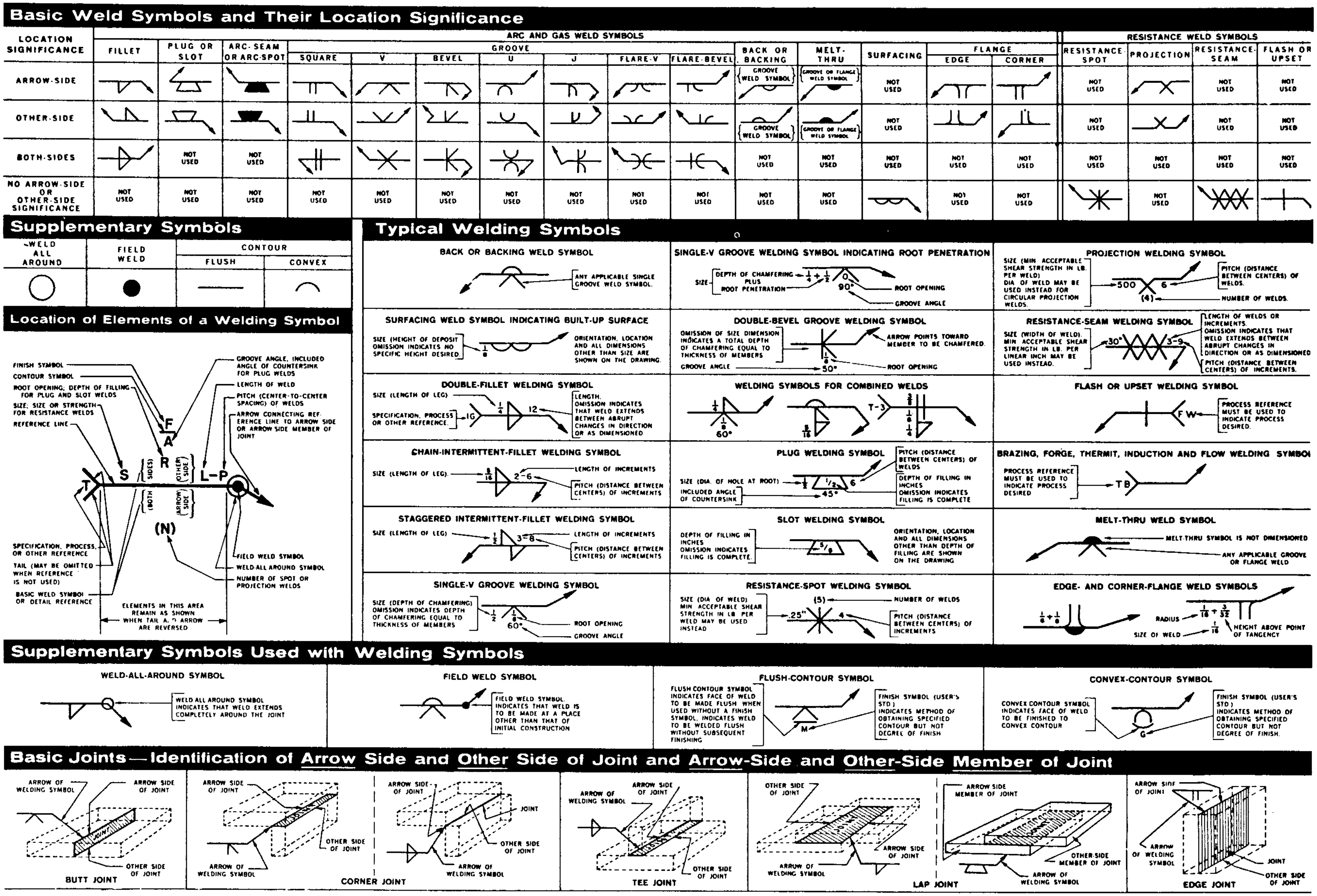


FIGURE 106. STANDARD WELDING SYMBOLS. (Copyright 1958 by the American Welding Society)

Section II. DISTORTION AND RESIDUAL STRESSES

231. INTRODUCTION

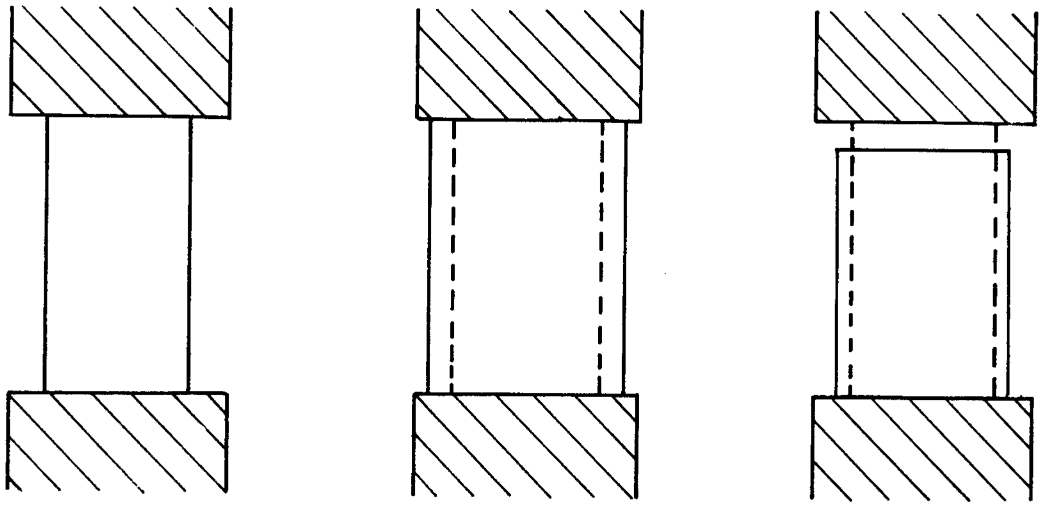
a. Distortion is the change in shape of a welded part as a result of welding. When the change or deformation is temporary, it is called elastic. Permanent change in shape is termed plastic deformation or plastic flow. The forces tending to cause distortion are present in every weld made, and unless proper techniques are used, the weldment may distort to the point where considerable time and money must be spent to correct it.

b. These forces are induced in a weldment by the unequal contraction of the solidifying weld metal and by the unequal expansion and contraction of the heat-affected zone during welding. The metal which has remained relatively cool during welding resists these expansions and contractions. This causes the weld metal to stretch and imposes opposite strains on the metal surrounding the weld. These opposing strains produce a system of stresses which are locked up within the weldment. These locked up stresses may be of two forms, residual stresses or reaction stresses. Residual stresses are those which remain in a weldment without external loading after the heat of welding has been dissipated. Reaction stresses are those due to the restraint of other members or parts attached to the weldment and which would not exist if these members or parts were removed.

232. CAUSES OF DISTORTION

a. When a bar of steel is heated thoroughly and uniformly, it will expand in all directions. If it is allowed to cool evenly without restraint of any kind, it will contract to its original shape and size. If the bar is restrained in any way during heating, it will not be able to expand in the directions of the restraint. A metal bar placed in a vice so that the jaws close against the two ends of the bar could not expand towards the ends when heated. Any expansion would have to be lateral as shown in Figure 107(a). When the bar contracts upon cooling, however, there is no restraint and it is free to contract in all directions. It does not return to its original shape and size but becomes shorter and thicker.

b. If heat is applied to only one side of a bar as shown in Figure 107 (b), expansion is localized and uneven. The surrounding cooler metal hinders expansion in all directions except on the surface. Therefore the heated metal, when it begins to cool and contract, undergoes plastic



a. Dimensional Changes Due to Even Heating and Cooling under Restraint.
Dotted lines show original size

b. Distortion of a Bar During Localized Heating.

c. Permanent Deformation After Cooling Following Localized Heating.

d. Approximation of a plate by Several Bars Laid Side-by-Side.

FIGURE 107. DISTORTION DURING EVEN AND LOCALIZED HEATING OF A METAL BAR

deformation analogous to that of the heated bar in Figure 107(a). This, in effect, makes the heated side of the bar shorter than the unheated side of the bar. Complete cooling of the bar then causes distortion as shown in Figure 107(c). A welded plate would be similar to several steel bars such as this laid side by side, as in Figure 107(d), in which the welding arc provides the localized heating.

c. In the preceding examples, distortion occurred due to plastic strain. As the bar is heated and tries to expand, compressive stresses build up in the bar. When these stresses become equal to the yield strength of the material, the stress level does not increase as heating continues. Instead, the stress remains nearly constant while the bar undergoes permanent deformation. If the stresses caused by heating the bar do not exceed the yield strength of the material, no permanent deformation will occur.

233. FORMATION OF RESIDUAL STRESSES

a. The physical laws of expansion and contraction explain the principal causes of distortion and residual stresses in welding operations. The metal is differentially heated during welding, subjected to drastic temperature graidents and becomes weaker and more easily deformed as it is heated. The coefficient of expansion and modulus of elasticity both vary with temperature. The coefficient of expansion rises with increasing temperature. This means that at higher initial temperatures a given temperature increase causes more expansion than at lower initial temperatures. The modulus of elasticity decreases as the temperature increases, which means that a greater amount of strain results for a given amount of stress as the temperature rises.

b. In most materials, the yield strength decreases at higher temperatures. In mild steel, for example, the yield strength is nearly zero above about 1000 F as shown in Figure 108. At temperatures above 1000 F, a steel bar may be easily stretched or twisted and may sag under its own weight if not supported.

c. From the preceding discussions, the change in compressive stress can be plotted for a steel bar heated under restraint. As shown in Figure 109(a), the compressive stress rises as the bar is heated. If the stress level does not exceed the yield strength of the bar, no permanent deformation will occur and the bar will return to its original shape after cooling. If the temperature is raised further, the stress level remains at the yield strength at all times as in Figure 109(b). At higher temperatures, the yield values fall to zero in accordance with Figure 108.

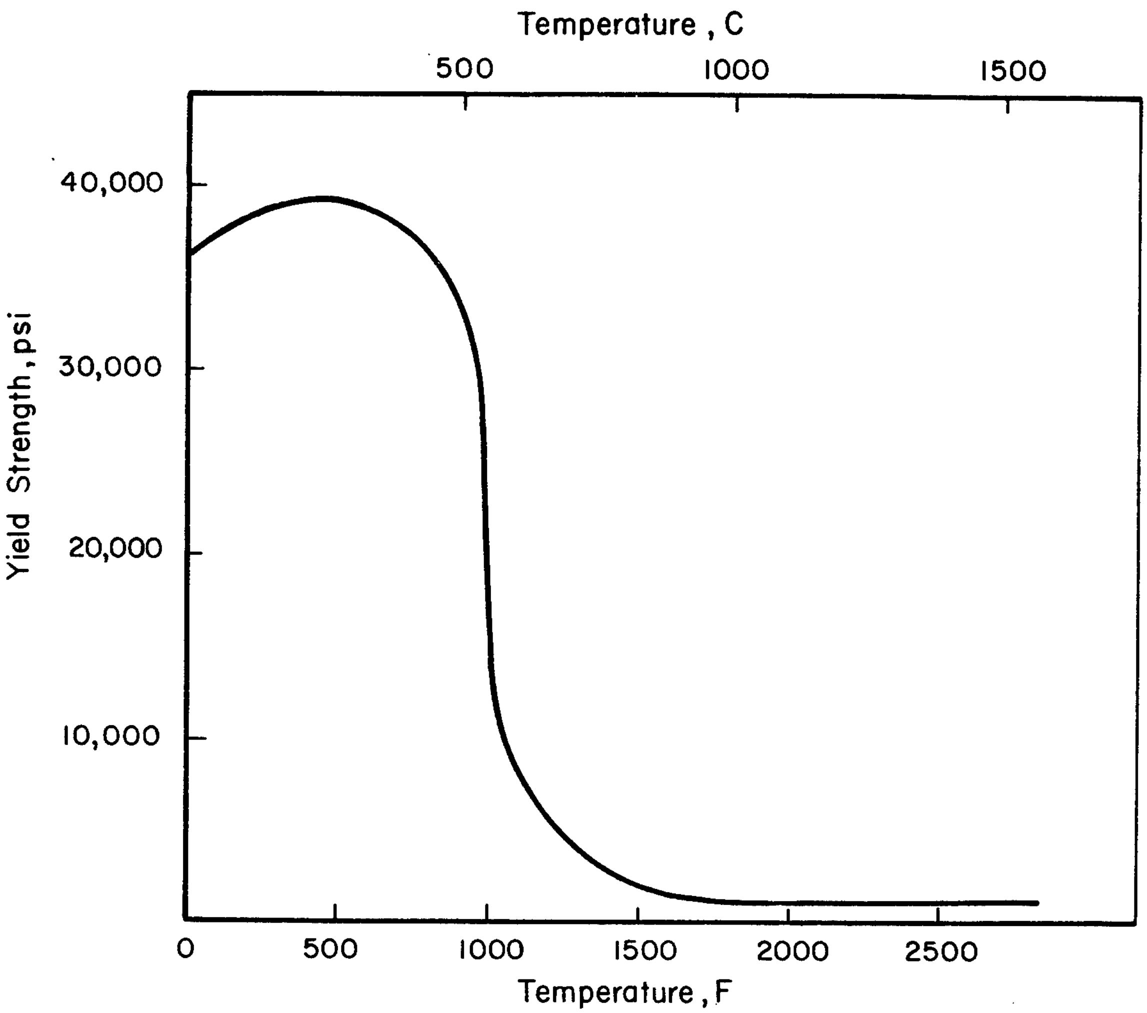
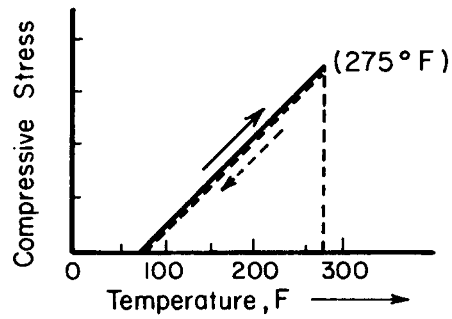
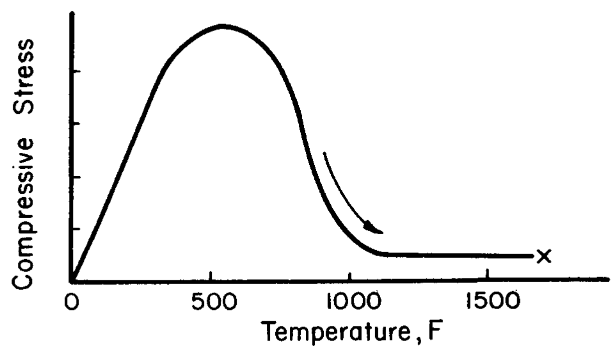


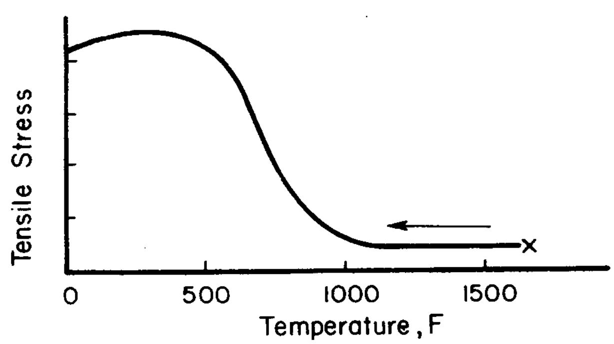
FIGURE 108. SCHEMATIC DIAGRAM OF VARIATIONS IN THE YIELD STRENGTH OF MILD STEEL IN TENSION OR COMPRESSION WITH VARYING TEMPERATURE



a. Compressive Stress in a Steel Bar Heated Under Restraint
The yield strength is not exceeded and no Deformation results.



b. Compressive Stress in a Steel Bar During Heating Under Restraint



c. Tensile Shrinkage Stress in a Steel Bar During Cooling Under Restraint

FIGURE 109. STRESSES IN A MILD STEEL BAR DURING HEATING AND COOLING UNDER RESTRAINT

d. If the bar heated under restraint in the jaws of a vise as in Figure 107(a) is cooled under restraint, tensile shrinkage stresses occur as in Figure 109(c). During cooling, the bar, being attached to the jaws of vise, cannot contract in length. The cooling results in permanent elongation of the bar just as heating resulted in shortening of the bar. At about 1000 F, the bar beings to regain elastic strength as shown by the rise in yield strength in Figure 108. When the bar reaches room temperature, therefore, it has been permanently elongated slightly and is under an elastic tensile stress equal to the yield point. While the bar remains in the vise, it has the same dimensions as it did prior to heating. Upon removal from the vise, the bar will contract in length and increase in diameter corresponding to the release of the yield point shrinkage stress if the bar returns to a stress-free state.

e. The bar completely restrained in the vise during heating and cooling illustrates qualitatively the origin of distortion and shrinkage stresses during welding. The bar is analogous to a short length of weld metal (tack weld) cooling between clamped plates to be butt welded. In the weld, however, the temperature is not distributed uniformly. The shrinkage of metal during solidification affects the formation of shrinkage cavities and hot tears, but has no direct effect on distortion and residual stresses.

f. Residual stresses may also result from transformations in the material. In steel for example, any changes in length due to transformations that occur above 1000 F will cause no shrinkage stresses because the yield strength is low. The expansion or contraction caused by the transformation is accommodated by plastic strains. However, if the transformation does not occur until low temperatures at which the yield strength is high, shrinkage stresses may arise. The areas of different shrinkage stresses due to transformations are on a microscopic scale, compared with the larger scale variations of shrinkage stresses due to upset during welding.

g. The rate of heating and cooling also affects the distortion and stresses in a bar. The shorter the time at temperature, the higher the yield strength of steel appears to be in the range of 800 to 1200 F. With rapid heating and cooling therefore, the amount of elastic strain that the material will undergo will increase compared with the amount of plastic strain. Less distortion or change of shape will occur. In welding, rapid cooling rates are associated with low heat inputs and narrow heat-affected zones. In the narrower heat-affected zones, less material undergoes plastic

strain and the amount of plastic strain is further reduced by the rapid heating and cooling. As a result, the distortion of the weldment is less.

234. SHRINKAGE DISTORTION

a. General. There are three classes of shrinkage distortion that are particularly important in welding: transverse distortion, longitudinal distortion, and angular distortion. These three types are shown in Figure 110.

b. Transverse Distortion. The shrinkage perpendicular to a butt weld depends primarily on the weld cross section. The larger the cross section, the greater the shrinkage. The transverse shrinkage also increases with increase in thickness for a given joint. Exact values for distortion vary with the degree of restraint, and extent to which heat flows from the weld into the plate. With respect to the degree of restraint, the shrinkage decreases as this increases.

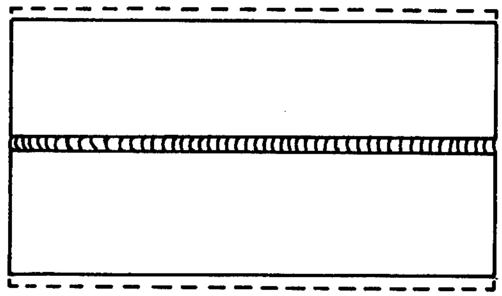
c. Longitudinal Distortion. The shrinkage parallel to a butt weld tends to reduce the width of the plate at the weld as shown in Figure 110(b). When thin plates are welded, residual compressive stresses occur in areas away from the weld and cause buckling. Buckling differs from bending distortion in that there is more than one stable deformed shape and the amount of deformation in buckling distortion is much greater.

d. Angular Distortion. Angular distortion is illustrated for U-butt and fillet welds in Figure 110(c). The shorter length of contracting weld metal at the root of the weld than at the surface accounts for the angular distortion.

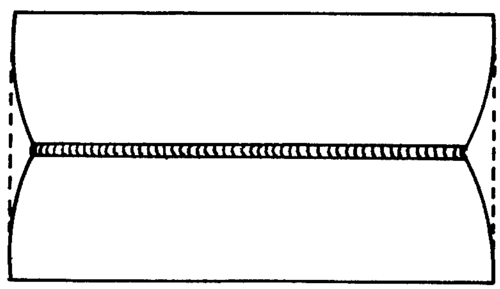
235. RESIDUAL STRESSES

a. General. The residual stresses in a butt-welded joint are caused by the contraction of the weld metal and the plastic deformation in the base metal near the weld during welding. The maximum residual stress in the weld area is determined by the expansion and contraction characteristics of the base metal and the weld metal during the welding thermal cycle and by the temperature-yield strength relationships of the base metal and the weld metal.

b. Residual Stresses in an Edge Weld. The formation and distribution of residual stresses are understood most easily in the case of an edge weld as in Figure 111. The metal close to the weld tends to expand



a. Transverse Distortion in a Longitudinal Butt Weld



b. Longitudinal Distortion in a Longitudinal Butt Weld

c. Angular Distortion in a Butt Weld and a Fillet Weld

FIGURE 110. FUNDAMENTAL DIMENSIONAL CHANGES THAT OCCUR IN WELDMENTS

in all directions when heated by the welding arc. It is restrained by adjacent cold metal and is upset as the bar was upset by the vise. During cooling, the upset zone attempts to contract but is again restrained by cold metal. As a result, the upset zone becomes stressed in tension. When the welded joint has cooled to room temperature, the weld and the upset region are under tensile stresses close to the yield strength. To balance the tensile stress at the edge, equilibrium conditions require that there be a region of tensile stress at the opposite unwelded edge and a region of compressive stress between the two tensile zones as shown in Figure 111.

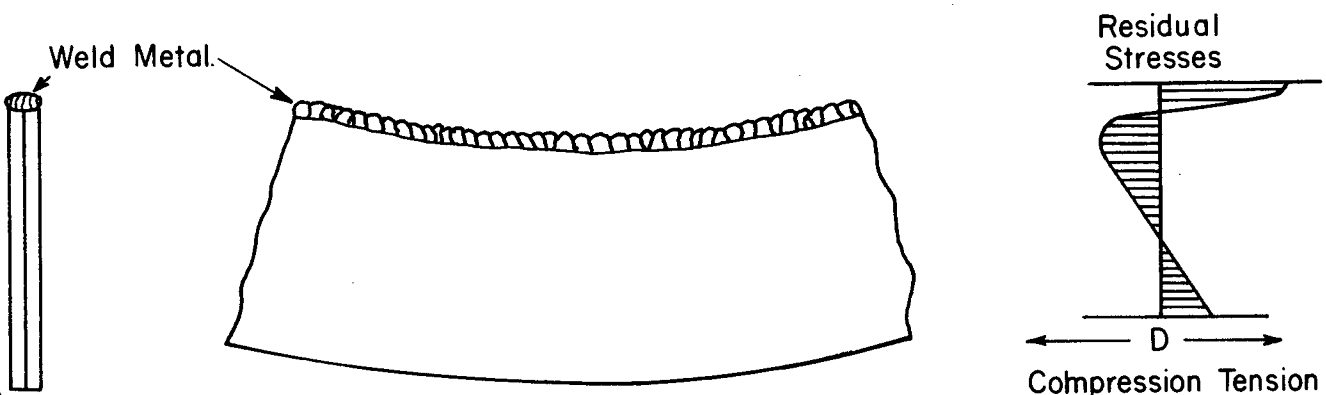
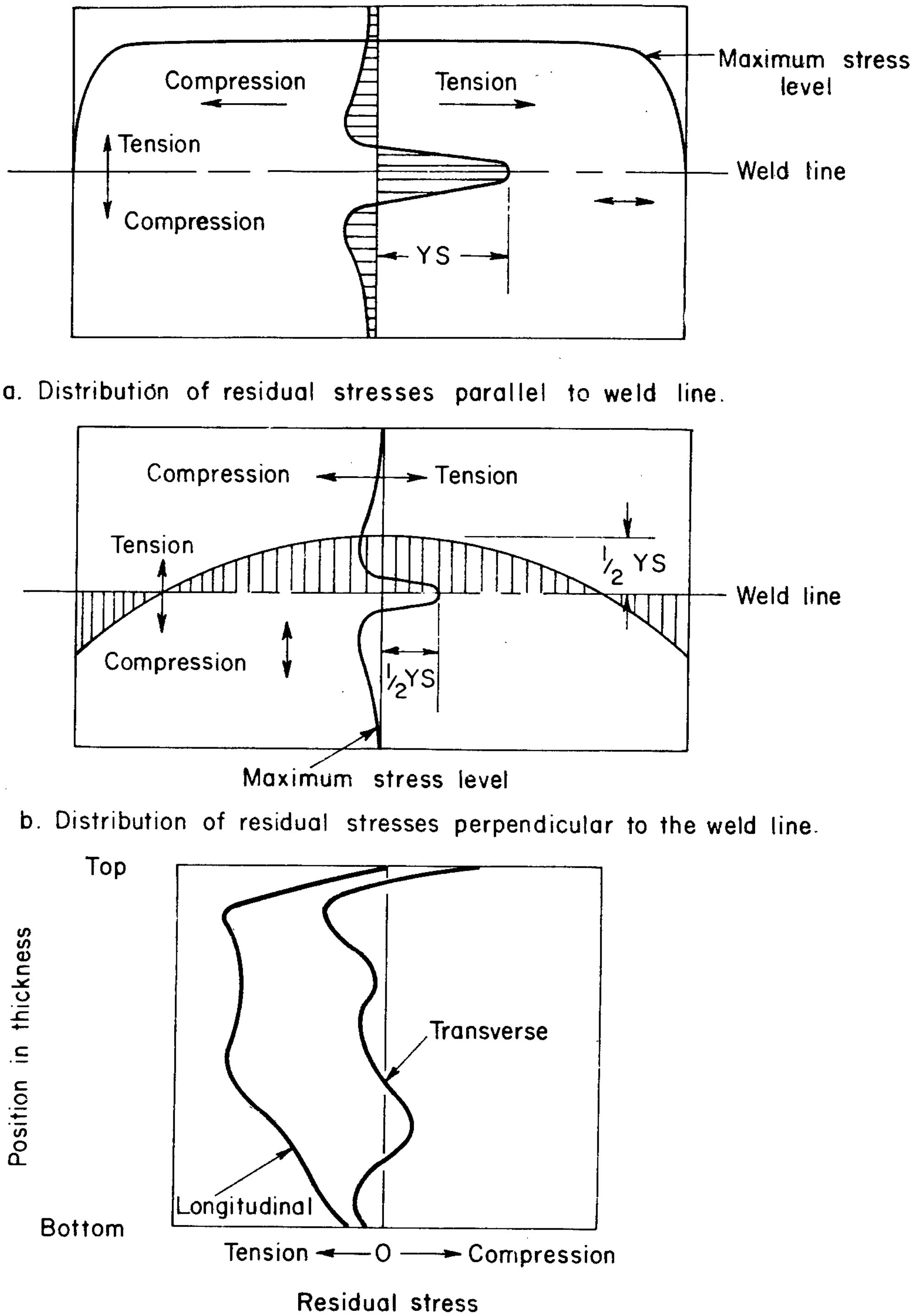


FIGURE 111. BOWING OF AN EDGE WELD

c. Residual Stresses in a Butt Weld. The residual stresses in a welded butt joint are more difficult to predict because stresses both parallel to and perpendicular to the welds must be considered. Typical distributions of residual stresses in a butt weld as determined experimentally are shown in Figure 112. The residual stresses parallel to the weld are tensile at the center of the weld and are close to the yield strength along most of the length of the weld. Moving from the weld into the base metal, the residual stress falls rapidly to zero and changes to compression. The residual stresses in the weld at right angles to the welding direction are maximum at the center of the plate. The transverse stresses at the ends of the weld are in compression to maintain equilibrium.



a. Distribution of residual stresses parallel to weld line.

b. Distribution of residual stresses perpendicular to the weld line.

c. Distribution of residual stresses in a thick butt-welded plate measured at the weld.

FIGURE 112. TYPICAL DISTRIBUTIONS OF RESIDUAL STRESSES IN A BUTT WELD

236. CONTROL OF DISTORTION AND RESIDUAL STRESSES

a. General. Distortion and residual stresses are different in nature but their causes are similar. Also, the means for controlling the amount of distortion and level residual stresses are similar. Six means of controlling distortion and residual stresses will be considered here: (1) design, (2) welding procedure and sequence, (3) fixturing, (4) preheating, (5) postweld heat treatment, and (6) peening. The last three areas listed are most applicable to the control of residual stresses.

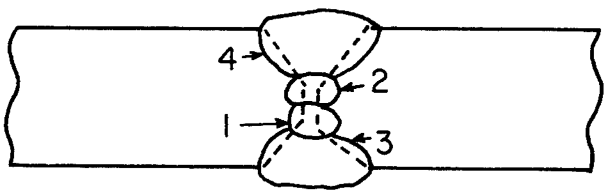
b. Design. Proper design of a welded joint can effectively reduce both the distortion and residual stress level in a weldment. The proper welding procedure begins with the proper edge preparation and fitup. A minimum bevel angle which allows adequate accessibility to the root of the weld should be used with a slight root opening. In this manner, a minimum amount of weld metal will be required. The addition of excess weld metal in the form of weld reinforcement causes distortion and contributes nothing to the strength and performance of the joint. Another means of reducing the effective shrinkage force is to place the weld as close as possible to the neutral axis of the weldment so that it does not have sufficient leverage to pull the plates out of alignment. The neutral axes of a cross section are the axes along which the cross section could be balanced on a knife blade.

c. Welding Procedure

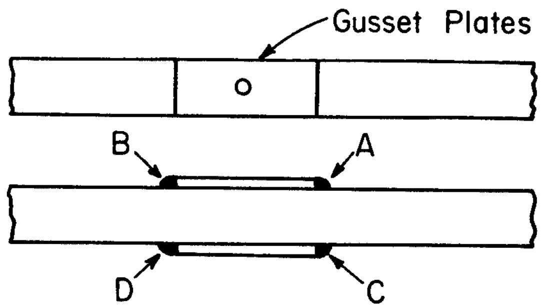
(1) The use of the proper size and number of weld beads will aid in controlling distortion. Transverse or angular distortion are less when a small number of large beads are used. If distortion in the longitudinal direction must be controlled, a larger number of small beads should be used. The small beads have a greater ability to stretch longitudinally as compared to a large bead.

(2) One shrinkage force may be balanced by another to reduce distortion by using the proper weld sequence. By placing weld metal at different points about the structure, the shrinkage of newly deposited weld metal counteracts the shrinkage forces caused by previous welds. Simple examples of this are shown in Figure 113. Distortion is prevented and residual stresses reduced by welding alternately on both sides of the neutral axis in the simple butt weld in Figure 113(a). In Figure 113(b), distortion is avoided by welding on

one end of each gusset followed by welding the other end rather than by first welding both beads on the same gusset.



a. Method of Alternating Weld Beads to Balance the Shrinkage Forces in a Butt Weld



b. Welding A-B-C-D in Order Given Causes Distortion

When A and C are welded and cooled, followed by B and D, distortion is eliminated.

FIGURE 113. METHODS OF ALTERNATING WELD BEADS TO BALANCE THE SHRINKAGE FORCES ABOUT THE NEUTRAL AXES

(3) The use of "backstep" welding and intermittent welding reduces both distortion and residual stresses. With the backstep technique, the general direction of welding progression is opposite to the direction in which the beads are deposited. This is illustrated in Figure 114. An intermittent weld is one in which the continuity of the welded joint is broken by recurring unwelded spaces. Both of these welding sequences tend to produce an internal stress pattern with numerous tension and compression areas balanced against each other. The result is that these stresses tend to equalize more readily and may not reach maximum values as high as those encountered in continuous welding.

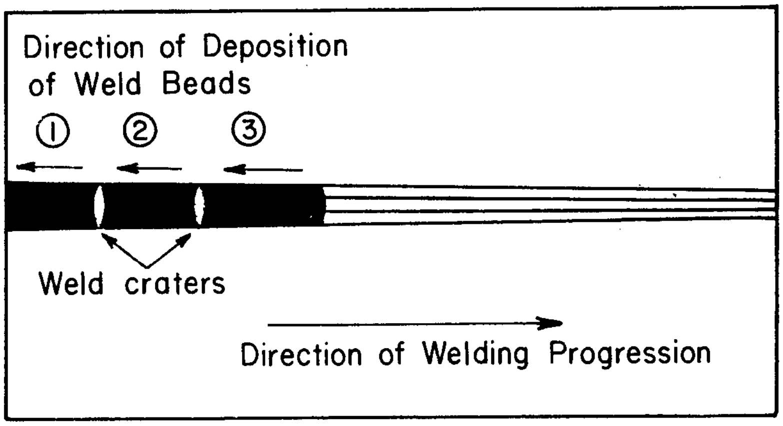


FIGURE 114. "BACKSTEP" WELDING TECHNIQUE

d. Jigs and Fixtures

(1) A welding jig is a device capable of holding the component parts to be welded in the proper relationship and with the proper fitup. A fixture is similar to a jig, except that it permits changing the position of the work during welding to place the joint in the most convenient position for welding.

(2) Jigs and fixtures may be used to hold the work in a rigid position during welding. In this way, the shrinkage forces of the weld are balanced with sufficient counter forces to minimize distortion. These balancing forces cause the weld metal to stretch, thus preventing most of the distortion. For example, if heavy plates are sprung away from the weld side, the counter force exerted by a jig overcomes most of the shrinkage tendency of the weld metal causing it to yield. A slight tendency for the weld to contract remains, however, due to the elastic residual stresses. When the plates are removed from the jig, this contraction tendency pulls the plates into exact alignment.

(3) More flexible jigs or fixtures may be used, however. The jig or fixture may position the parts out of alignment before the weld is deposited. The jig may be sufficiently flexible to allow the parts to be brought into correct alignment as the weld shrinks.

e. Preheating. Preheating is often an excellent means of minimizing residual stresses and is especially helpful when welding on heavy sections and on any thickness of hardenable materials. Preheating may be used to prevent the formation of hard zones and reduce shrinkage stresses by preventing or delaying transformations in the material. Also, higher preheat temperatures reduce the yield strength of the material as in Figure 108. The residual stresses would thus have a lower maximum value than those caused by welding on nonpreheated material. Preheating must be carefully planned and controlled. It is very important that uniformity of preheat temperature be maintained, as well as the use of the correct temperature. Overheating or underheating may produce other residual stresses. Localized preheating may induce additional residual stresses rather than achieving a reduction of stress level.

f. Stress-Relief Heat Treatment. Stress-relief heat treatment involves the uniform heating of a structure or portion of a structure to a sufficient temperature to relieve the major portion of the residual stresses, followed by uniform cooling. The structure must be held at the stress-relief temperature long enough for the entire structure to reach a uniform temperature. The terms normalizing, annealing, etc., are often erroneously used for this application. The principles of stress-relief heat treatment of steel can be understood by reference to Figure 108. Stresses above the yield strength of a material will cause upsetting of that material and attendant lowering of the stresses. When heated above 1000 F, the yield strength of steel drops to a low value. Any residual stresses present in the material must then be at this level through movement and upsetting of the material. The normal heating time for a steel structure is 1 hour per inch of cross-section thickness. By uniform cooling, the material experiences little restraint and the residual stress level remains at a low value throughout the structure.

g. Peening. Peening is the mechanical working of metals by means of hammer blows. Peening controls distortion and residual stresses by stretching the weld bead and counteracting its tendency to shrink as it cools. It is most effective when done on heated materials. However, there is no good way to determine the amount of peening which should be done. Overpeening may cause cracks in the weld metal. Peening stresses the metal immediately below the tool far beyond the elastic limits while metal farther away is stressed much less. Thus, peening is at most a highly inaccurate means of reducing residual stresses.

237. EFFECT OF RESIDUAL STRESSES ON WELDMENT PERFORMANCE

a. General. Much research has been conducted on the effects of residual stresses on weldment performance. The areas which have received the greatest interest have been ductile-brittle fracture, fatigue, failure, buckling and delayed and stress-corrosion cracking.

b. Ductile-Brittle Fracture. It has been established that the effects of residual stresses are negligible when the fracture occurs in a ductile manner after the structure has exhibited considerable plastic deformation. This is, the fracture strength, elongation and energy absorption of a welded structure are neither raised nor lowered by the presence of residual stresses when the fracture is ductile. If, due to unfavorable structure of multiaxial stresses, the steel is incapable of undergoing permanent deformation without cracking, the residual stresses may bring the part to premature failure. Research results indicate that residual stresses must be present for brittle fractures to occur at very low stresses.

c. Fatigue Fracture. Much research has been done on the effects of residual stresses on the fatigue fracture of metal structures. The effect of residual stress is still a matter of debate, however. A number of investigations have reported that the fatigue strength (the number of cycles to fracture at a given load or the endurance limit) increased when specimens had compressive residual stresses, especially on the specimen surfaces. A number of other studies, however, indicate that the effects of residual stress on the fatigue strength of weldments are negligible.

d. Buckling. Failures due to instability, or buckling, sometimes occur in metal structures composed of slender bars and/or thin plates when they are subjected to compressive axial loading, bending or torsional loading. It is known that residual compressive stresses decrease the buckling strength of a metal structure. Initial distortions caused by residual stresses also decrease the buckling strength.

e. Delayed and Stress-Corrosion Cracking. It has been long recognized that cracking can occur in weldments, even without external loading, when the material has been embrittled by metallurgical processes or by being exposed to certain environments. Delayed cracking is generally recognized as due to hydrogen absorption in the material at high temperatures, as explained in Paragraph 14c of Chapter 2. As the hydrogen is forced out of solution during cooling, it gathers at the sites of high tensile residual stresses, since this is where the metal atoms are farthest apart. This further stresses the metal and promotes cracking. Stress-corrosion

cracking will take place at the sites of high residual tensile stresses in materials sensitive to stress-corrosion cracking.

Section III. FACTORS INFLUENCING CHOICE OF WELDING PROCESSES

238. INTRODUCTION

In some cases, like stud welding, the choice of the process is dictated by the application. Generally, the selection of a welding process for a specific application involves the consideration of several factors. Some of these factors will be discussed in this section.

239. AVAILABILITY OF EQUIPMENT AND EXPERIENCE

a. In general, it is best to use processes for which the equipment is available and with which personnel are experienced. This is true not only for economic reasons but because familiarity with the equipment and process generally aids in obtaining the desired weld quality.

b. There are, however, situations where the introduction of a new process may provide benefits that offset the disadvantages of purchasing new equipment and training personnel.

c. One such example might be where the new process offers such significant improvements in production rate and weld quality that it offsets the cost and time involved in procuring the equipment and training personnel. The best time, but not necessarily the only time, to consider such changes is during the design of the product. Then, the weldment and joint designs may be tailored to the new process. Sufficient time is also allowed to gain experience prior to commencing production.

d. A change to a new process might also be desirable to offset a shortage in trained operators. For example, semiautomatic gas metal-arc processes are usually easier to teach to a novice than the shielded manual-arc process. Therefore, by switching to the semiautomatic process, personnel might be phased into production more quickly, saving valuable time.

e. When a process is being selected, then, first consideration should be given to currently used processes. New processes, however, should not be discounted until all of their possible advantages and benefits have been considered.

240. WELDING POSITION

a. As indicated in Paragraph 227b, some welding positions are preferred over others. Good design and fabrication procedures require that welds be performed in the flat position whenever possible. Out-of-position welding, when required, limits the number of applicable processes.

b. For most engineering materials, the only arc-welding processes suitable for out-of-position welding are shielded metal-arc, dip transfer, gas metal-arc, and pulsed arc. Of these, the dip-transfer and pulsed-arc processes are preferable to the shielded metal-arc process because of improved economy and operator control of welding parameters. Both of the semiautomatic processes, however, require good operator technique to prevent lack-of-fusion defects at the joint sidewall when welding at the low heat inputs required for out-of-position welds. Good quality control requires that operators be thoroughly qualified in these processes before they are committed to production.

c. For special materials or applications, the gas tungsten-arc process may also be used for out-of-position welding, where it is capable of producing welds of the highest quality. The gas tungsten-arc process is not generally used, however, because it is not economically competitive with the gas metal-arc processes.

d. The electroslag, electrogas, and vertical submerged-arc processes are suitable for joining heavy thicknesses (1 to 5 inches) of common ferrous engineering materials in the vertical position only.

241. GEOMETRY OF PARTS

The geometry of a part is considered to include (1) the size and "positionability" of the weldment, (2) the thickness of the members being joined, and (3) accessibility to the joints.

242. SIZE AND "POSITIONABILITY"

a. If a weldment is designed or can be positioned so that all of the welds are performed in the flat position, then any of the arc-welding processes may be used, material characteristics permitting. When this option is available, the process should be chosen that will accomplish the desired welds most economically.

b. Special advantages may be gained by positioning the weld in the vertical position to permit using the electroslag, electrogas, or vertical submerged-arc processes. The processes are economical, however, only for heavy thicknesses and can be used only on ferrous materials whose properties are not degraded by the processes' characteristic high heat input.

c. Whenever out-of-position welds are required, the choice of processes is limited to those described in the preceding section.

243. THICKNESS OF MEMBERS BEING JOINED

a. For each material in a given thickness range, there are certain optimum processes.

b. For heavy-thickness weldments in the flat position in all materials, the semiautomatic or automatic processes such as gas metal-arc, flux-cored wire, and submerged-arc are preferred, material characteristics permitting, because of their high deposition rates. Out-of-position welds, of course, greatly reduce the number of applicable processes. For short-length welds, the shielded-metal-arc process may also be suitable.

c. For heavy weldments (1 to 5 inches) in ferrous materials in the vertical position, the electrogas, electroslag, and vertical submerged-arc processes are superior, provided their characteristically high heat inputs are not detrimental to the properties of the material being joined.

d. Sheet thickness materials may be welded using the gas tungsten-arc, dip-transfer, or pulsed-arc processes. The gas metal-arc processes are preferable for thicknesses down to 0.060 inch inclusive, because of their faster finishing rates. The gas tungsten-arc process is better for thicknesses under 0.060 inch because of the lower currents that can be maintained.

e. For welds in very thin materials ($<$ 0.030 inch), the electron-beam, needle-arc plasma, and laser welding processes are preferred. The size of the weldment that can be performed with the electron-beam process is limited by the size of the vacuum chamber. The needle-arc plasma process can be used in the atmosphere and so can accommodate a wide range of weldment shapes and sizes. The laser welding process is practical only for very special applications.

244. ACCESSIBILITY OF JOINT

a. In a small number of cases, limited accessibility to the joint may prevent using the preferred process because the equipment cannot be fitted into the available space.

b. Electron-beam or laser welding may be used to weld some inaccessible joints, since they require only a line of sight to the joint being welded. In special cases, shielded metal-arc welding can be used by bending the electrode to fit the restricted area. Special guide tubes may also be designed for gas metal-arc welding in restricted spaces.

245. QUALITY REQUIREMENTS

The quality requirements for a weld can be considered to consist of essentially two types of requirements: (1) the allowable-defect incidence and (2) the mechanical-property requirements. The mechanical properties of the weldment are often determined by the metallurgical effects of the process on the material.

246. EFFECT OF PROCESS ON DEFECT INCIDENCE

When properly performed, all of the processes are equally capable of producing defect-free welds. There is a tendency toward higher defect levels with some of the processes because of the large effect operator technique has on the quality of the weld. As mentioned previously, dip-transfer and pulsed-arc welding at low heat inputs requires special care from the operator to ensure that good sidewall fusion is obtained. With low-hydrogen-shielded metal-arc electrodes, a short arc length must be maintained to keep the hydrogen content of the weld low. Processes utilizing protective slags such as flux-cored wire, shielded metal-arc or submerged-arc welding require more stringent interpass cleaning than do the inert-gas-shielded processes to prevent entrapment of slag in the weld. Shielded-metal-arc welds may have a higher defect incidence than inert-gas shielded welds because of the larger number of stops and starts. When such occurrences are anticipated to be a problem, alternative processes should be selected where possible.

247. METALLURGICAL CONSIDERATIONS

Processes are more often selected or rejected because of their effects on the metallurgy of the weld rather than because of a tendency towards higher defect incidence. The effect of a process on the metallurgy of the weld must be considered when (1) heat input must be regulated to preserve

base-metal mechanical properties, (2) hydrogen induced into the weld metal by the welding process can cause cracking, (3) efficient alloy transfer across the arc is required, (4) reactive metals are welded, and (5) mechanical properties of the weld are dependent on shielding. Most of these cases are involved with the heat input and shielding characteristics of the various processes.

248. HEAT INPUT

a. When many of the new high-strength, low-alloy steels are being welded, it is necessary to maintain the heat input to the base metal from the process below a certain value to prevent degradation of the base-metal properties in the weld heat-affected zone. In some of these materials, excessive heat input may cause overtempering of martensitic structures, causing a loss in strength. In others, incorrect heat input can cause the formation of microstructures which reduce the impact strength of the base metal or cause a tendency towards cracking. High heat inputs also tend to cause large heat-affected zones.

b. The high-deposition-rate processes, such as flux-cored electrode, submerged-arc, electroslag, electrogas, or vertical submerged-arc, are not suitable for welding heat-input-sensitive materials because of their characteristic high heat input. Shielded metal-arc, gas tungsten-arc, gas metal-arc (particularly in the forms of dip transfer and pulsed arc) are all quite suitable for heat-input-sensitive materials. Electron-beam and laser welding are also excellent where practical.

c. The high-deposition-rate processes generally produce welds with a coarse, dendritic structure because of the large size of the weld puddle produced. Such welds generally have poor impact strengths and require post-weld heat treatment to develop optimum properties. Therefore, these processes should not be used where good impact strengths are required in the as-welded condition.

249. HYDROGEN-INDUCED CRACKING

a. Some steels are susceptible to underbead cracking when martensitic microstructures are formed in the heat-affected zone. Underbead cracking occurs when atomic hydrogen induced by the welding process migrates to the grain boundaries and recombines there, generating large stresses. The tendency toward underbead cracking can be reduced by adjusting the heat input so that cooling rates are too slow to permit martensitic structures to form and by eliminating the source of hydrogen.

b. The common cellulosic-shielded metal-arc electrodes generate large amounts of hydrogen and therefore should not be used for welding underbead-crack-sensitive materials. Such materials can be welded with either low-hydrogen-shielded metal-arc electrodes or by an inert-gas shielded process, such as gas metal-arc welding.

250. ALLOY TRANSFER

Some alloying elements, such as titanium and columbium, are difficult to transfer across an arc because they are easily oxidized. If steels containing such easily oxidized elements are welded by either the shielded metal-arc process of the submerged-arc process, large losses may occur because of oxidization by gases present in the arc or by the slag itself. Inert-gas-shielded processes can minimize these losses.

251. REACTIVE METALS

a. Many of the new speciality materials, such as titanium or zirconium, are highly reactive with atmospheric gases when molten.

b. This type of material can be joined by either gas tungsten-arc or gas metal-arc welding using a sealed chamber. The chamber is first pumped free of atmospheric gases with a vacuum pump and then backfilled with an inert gas.

c. Electron-beam welding is also an excellent process for joining reactive metals.

252. MECHANICAL PROPERTIES DEPENDENT ON SHIELDING

In some ultrahigh-strength steels, the impact strength of the weld metal is decreased by the presence of small amounts of oxygen induced during welding. Inert-gas-shielded processes are generally used for these materials. For such materials, gas tungsten-arc welding may produce welds with better impact properties than gas metal-arc welding because the addition of small amounts of oxygen to improve the stability of the gas metal-arc is not required for the gas tungsten-arc.

253. COST

a. When a process is being selected, the overriding factor in the majority of cases is cost. In general, the process that will produce the required welds most economically should be selected.

b. In general, reduced costs can be achieved by using semiautomatic or fully automatic processes in place of shielded metal-arc, manual welding. Some of the criteria for selecting either manual, semiautomatic, or automatic welding are given below.

(1) Manual. Manual welding should be used for (1) very short welds, (2) nonrepetitive jobs, (3) jobs where fitup cannot be controlled, and (4) irregularly shaped weldments.

(2) Semiautomatic. Semiautomatic welding should be used (1) for jobs where continuous wire feed would increase percentage of arc time, (2) for work that is repetitive enough so that proper procedure can be marked out and proper skill is acquired, (3) for complicated shapes or extremely large weldments, which make fixturing for full automatic too difficult, and (4) when contour and fitup is not accurate for full automatic welding.

(3) Full-Automatic. Full-automatic welding should be used for highly repetitive jobs that can be fixtured.

c. When a semiautomatic or full-automatic process is being selected, the four factors that exert a major influence on the cost of the process should be considered. These factors are: (1) the joint preparations required, (2) the type and size of filler wire required, (3) type of shielding gas required (if any), and (4) the amount of finishing required. These factors should be considered and compared for each of the candidate processes.

(1) Joint Preparation. As explained in Section I, Chapter 4, there are certain optimum joint preparations for each process. Generally, one joint preparation will cost less than others. The process selected should use the most economical joint preparation unless there are extenuating circumstances, such as savings of expensive filler metal.

(2) Wire Diameter. In general, the process that employs the largest practical diameter wire should be used. Wire of larger diameter not only increases deposition rates, but it is cheaper to buy because of reduced finishing costs.

(3) Shielding. The cost of the shielding gas in inert-gas-shielded processes can account for a significant portion of the cost of the process. Flux-shielded processes are cheaper, in general, but the lower material costs may be offset by the increased cost of cleaning the joint between passes and after the weld is completed.

(4) Interpass and Post-Weld Cleaning. The amount of interpass and/or post-weld cleaning required can also have a significant effect on the cost of a process. In such cases, the cost of gas for the inert-gas-shielded processes may be more than offset by the cost of cleaning the slag left by flux-shielded processes, particularly for multipass welds. Savings can also be realized by selecting processes that minimize spatter and attendant removal operations.

CHAPTER 11

QUALITY ASSURANCE

Section I. GENERAL

254. DEFINITION

Quality assurance is the function of management that consists of a planned and systematic pattern of actions by which the conformance of a product to the requirements of users is predicted, is designed in material during the development phase, and is assured for the life of the product.

255. APPLICATION TO WELDING

a. General. Quality assurance as applied to welded products has many facets. Quality must be built into the product, starting at the earliest concept phases of design and maintained throughout detail design and fabrication. Some major steps in quality assurance of welded products are discussed below.

b. Materials. Quality assurance starts with selection of materials. Not all metals are readily welded. Selection of difficult-to-weld materials places a burden on subsequent quality-assurance functions, and therefore should be done only after careful consideration of alternatives.

c. Design. When a welded product is being designed, consideration must be given to providing accessibility for welding. Placing welds in locations that are hard to reach or in locations which preclude the use of more reliable welding processes and procedures can penalize product quality. Proper design to achieve maximum joint strength with simplest welding procedures is of course important for reasons of both economy and quality assurance.

d. Production Control. This step in quality assurance takes in a multitude of operations. Control and proper documentation of materials, procedures, and logistics is, of course, of major importance in assuring product quality. It is extremely important to be sure proper materials, procedures, and equipment are available and used at each step of fabrication.

e. Welding Procedures. Preparation of welding procedures, either formal or informal, is usually not thought of as a quality-assurance function. Nevertheless, proper selection and testing of procedures prior to production and effective transmittal of these procedures to the welding operation is an important part of the overall quality-assurance program.

f. Welding Operation Control. It is important to assure that welding operators are qualified to do the particular welding operation on which they are employed. This may or may not involve a formal qualification test. The welding operator, probably more than any other person, is responsible for building the quality into the joint on the first attempt. Others can detect defective welds and have them repaired to assure that the quality is finally obtained. The primary responsibility for obtaining quality welds initially must rest on the welding operator, who must follow proper procedures, use proper materials, keep his equipment in good working order, and, above all, recognize trouble when it occurs and correct it before defects occur in the weld.

g. Nondestructive Testing. The nondestructive-testing functions of weld-quality assurance starts with the acceptance tests for incoming base materials and welding consumables, continues with the in-process nondestructive tests, and concludes with the final acceptance tests. The nondestructive-testing function is often the only quality-assurance function recognized by most welding personnel. There is a tendency to perform welding operations at levels corresponding to the extent of nondestructive testing to which the weld will be examined. The more thorough the testing, the more carefully the welding will be controlled.

256. QUALITY-ASSURANCE RESPONSIBILITY

a. General. The responsibility for quality assurance rests with all who are involved before, during, and after welding. As indicated in the preceding paragraph, a good quality-assurance program is the responsibility of all people involved in the fabrication of a product. It cannot be done only by the so-called "quality-assurance" personnel. The ultimate responsibility of the quality-assurance personnel is to verify that the product meets certain standards at the time it is completed. This may require making a number of repairs. Best quality is obtained when all personnel cooperate to produce the necessary quality during the initial construction.

b. Welding Engineer. It is the responsibility of the welding engineer to set up welding procedures for each application. These procedures

should describe in detail the steps and precautions a welding operator must follow to produce an acceptable-quality weld under a given set of conditions imposed by the application. The welding engineer bases his decision on prior knowledge and experience, and may verify the adequacy of the procedure by conducting procedure qualification tests. A procedure-qualification test is usually made on a small section of the material to be welded. It is welded in the laboratory under simulated-production welding conditions.

c. Welders. The welder or welding operator is responsible for assuring that the welds made in a particular application are done according to the specified welding procedure. The welder's ability to make the welds may be tested by means of a personnel qualification test. Passing this test shows that the welder is capable of making satisfactory welds in the laboratory by the established welding procedure. The welder must, however, maintain this quality on the actual weldment in the shop or field.

Some potentially dangerous conditions induced by welding cannot be detected by standard testing equipment or testing techniques now used in the field. The welder, or welding operator, may observe these conditions during welding, or may inadvertently cause them. When this happens, it is his responsibility to stop welding and take proper corrective measures. Every welder, or welding operator, should be his own inspector, not allowing himself to make welds below his capability or understanding.

d. Quality-Control Personnel.

(1) The quality of the final product produced by the contractor rests with his quality-control personnel. It is their responsibility to make sure that materials and equipment meet the required specifications. They are responsible for every manufacturing operation through the final step in production.

(2) Quality-control personnel must know the particular properties of the material that enable it to perform satisfactorily in service. They must know the effect of the welding process on the properties of the material and they must be cognizant of the conditions to which the part will be subjected in service. Quality control and inspection overlap; if quality-control personnel do their job properly, inspection personnel will find very few rejects.

e. Inspector. The inspector, whether he works for the fabricator or for the government, is a representative for the government. He must uphold all quality criteria agreed to by the company and the government. The inspector must have an understanding of the service conditions to which the weldment will be subjected. He must know the limitations of the testing methods, material, and the welding process. He is responsible for the final acceptance of the completed product. If he has any doubt about the performance of the weldment in service, he should take the appropriate steps to have the imperfections corrected, or if necessary, the weldment rejected.

f. Importance of Cooperation.

(1) It has already been mentioned that the best quality is obtained when all personnel cooperate throughout the various stages of production to produce acceptable quality during the initial fabrication. It is true that, in general, repairs can be made to a part which is otherwise unacceptable to remove rejectable defects and make the part acceptable. In practice, this is costly and may have other undesirable effects.

(2) Repairing welds involves extra machining or grinding to remove the defective weld. Most often this is a manual operation involving extensive grinding time. Extra nondestructive testing may be required to insure the defect is removed and the repair weld is sound. These operations are costly in time and money.

(3) The repair weld is a "cut-and-try" operation. The original machined joint is no longer present. Instead the weld must be deposited in some groove whose dimensions are more or less dictated by the amount of metal removal required to remove the defect. The standard welding procedure no longer applies to this joint. Quality of repair welds therefore are more dependent on the welder's skill. Often the repair weld must be made under conditions of limited accessibility or with process limitations that did not exist in the original weld. As a result, the chances of having new defects in the repair weld are probably greater than they were in the original weld. Repair welds should therefore not be made unless they are absolutely essential.

(4) Repair welds can have detrimental effects on the part. Repeated welding in one area of a repair can produce unacceptable distortion. Deterioration in weld heat-affected-zone properties can also occur in some materials leading to loss of strength, toughness, or corrosion properties. Planning for repair welding therefore should receive the same attention as the original weld by the welding and quality-control personnel.

257. LEVELS OF ACCEPTANCE

a. General. Weldment acceptance criteria are based on previous experience and the service conditions to which the weldment will be subjected. The weld must be adequately safe but not overly expensive. Since cost generally increases with increased quality-assurance provision, levels of acceptance must vary in the interest of economy from practically none to very extensive quality-assurance tests depending on service applications of the part. The levels of acceptance for welds may be classified into four groups, as discussed in the following paragraphs.

b. Minimum Level. Many weld applications require no formal inspection. This is often true for attachment welds, e.g., welds used to attach lugs to a noncritical area of a part. The welder may or may not have to be qualified for this weld operation. Visual or dye-penetrant inspection may be required, but there is no requirement for inspection of internal, subsurface weld defects.

c. Spot-Check Criteria. Certain weld applications require a spot check for internal weld defects. Certain areas and percentage of total weld length must be radiographed. The welder will usually have to be qualified for this type of application. This type of inspection is generally used in less critical applications.

d. Full Inspection-Commercial Quality. For applications which could produce loss of life or extensive property damage if failure occurs, weldments must be fully inspected. This usually involves complete radiography of all welds, qualification of procedures and personnel, and maintenance of records to assure that practices meet standard codes.

e. Full Inspection – Critical Applications. For certain application such as nuclear-reactor, submarines, and aerospace applications, critical welds must be fully inspected, and precautions--such as the use of approved procedures and personnel--are required, as in the case of full

inspection of commercial-quality applications described above. However, additional restrictions are usually added in the applicable Government or commercial specifications for these applications. Acceptance levels for weld flaws are generally more stringent. The materials permitted for use in these applications are more closely defined. The extent of testing is usually increased and may include more thorough testing of incoming materials as well as more in-process weld inspection.

Section II. QUALIFICATION TESTS

258. GENERAL

Two types of qualification tests are used as part of weld-quality-assurance programs. These are the welding-procedure-qualification and welding-personnel-qualification tests. As the names imply, the former is a test of the procedure and the latter is a test of the welder or welding operator.

259. PROCEDURE QUALIFICATION

a. Purpose. The purpose of the procedure-qualification test is to demonstrate that welds with suitable mechanical properties and soundness can be made by a certain procedure.

b. Method. In procedure-qualification tests, small test plates with the same chemical composition as the production weldment are welded by the welding procedure proposed for use on the actual weldment. These test plates are then tested to determine whether the weld has adequate soundness and properties to meet acceptance standards of the production weld. The joint geometry, welding process, welding parameters, filler metal, and shielding materials, and the welding position used in making the procedure-qualification plate, are the same as or equivalent to those used in the actual production weldment. The requirements for qualifying a welding procedure for a given application are governed by the welding codes covering that application.

c. Testing.

(1) The procedure plates are usually nondestructively tested by the same tests required for the production weld. The procedure plate must meet the nondestructive-test acceptance standards of the applicable code.

(2) Procedure-qualification plates are normally tested by tensile and bend tests. Additional tests required for some welds are nick-break tests, impact tests, and metallographic examination.

(3) Tensile-test specimens are removed so that the long axis of the specimen is transverse to the welding direction and is centered on the weld centerline, as is shown schematically in Figure 115. The actual specimen geometry varies widely to meet requirements of various welding codes. Specimens may be round bars or rectangular in shape. The latter type may or may not have a reduced section at the center and may or may not have weld reinforcement removed. To be acceptable, the tensile strength obtained on testing the transverse-weld tensile specimens must exceed minimum values specified in the welding code for that type of material. The primary purpose of the tensile test therefore is to demonstrate that the weld metal deposited by the selected procedure has the necessary strength to meet design requirements.

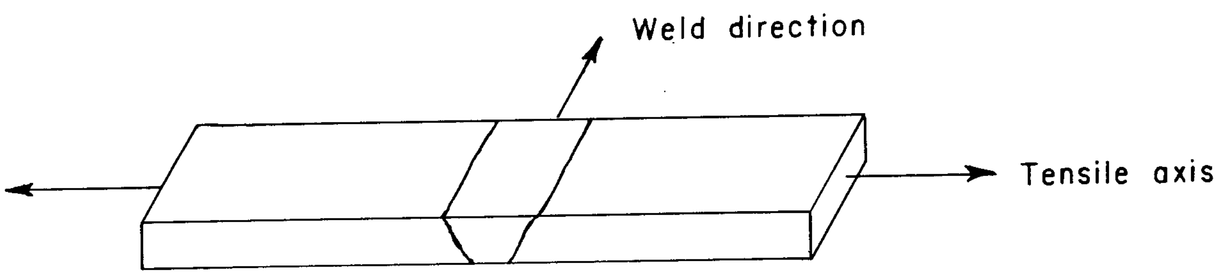


FIGURE 115. SCHEMATIC REPRESENTATION OF TRANSVERSE WELD TENSION SPECIMEN

(4) Three types of bend tests are used in procedure-qualification tests. Root-bend and face-bend tests are used on thin materials up to about 3/8 inch thick. Side/bend tests are used for thicker materials. These names refer to the surface that is stretched in tension during bending. In the root-bend test, the bottom of the weld is put in tension. In the face-bend test, the top of the weld, and in the side-bend test, a transverse cross section, is put in tension by the bending.

The specimens are machined or ground to remove the weld reinforcement. They are then bent around a die of specified radius, as shown in Figure 116 into a U shape. The amount of elongation of the tension surface is determined by the relationship between the specimen thickness, t, and the die radius, R. Normally, a 3/8-inch-thick specimen is bent around a 1-1/2-inch-diameter die to produce about 20 percent elongation in the tensile surface of the specimen. The bend test indicates the ductility of the weld metal and detects small defects in the weld, which tend to open up and become readily visible after the bend test. The acceptance criteria usually used for bend tests is that no fissures exceeding a specified length (usually 1/8 inch) are present on the tension surface after bending.

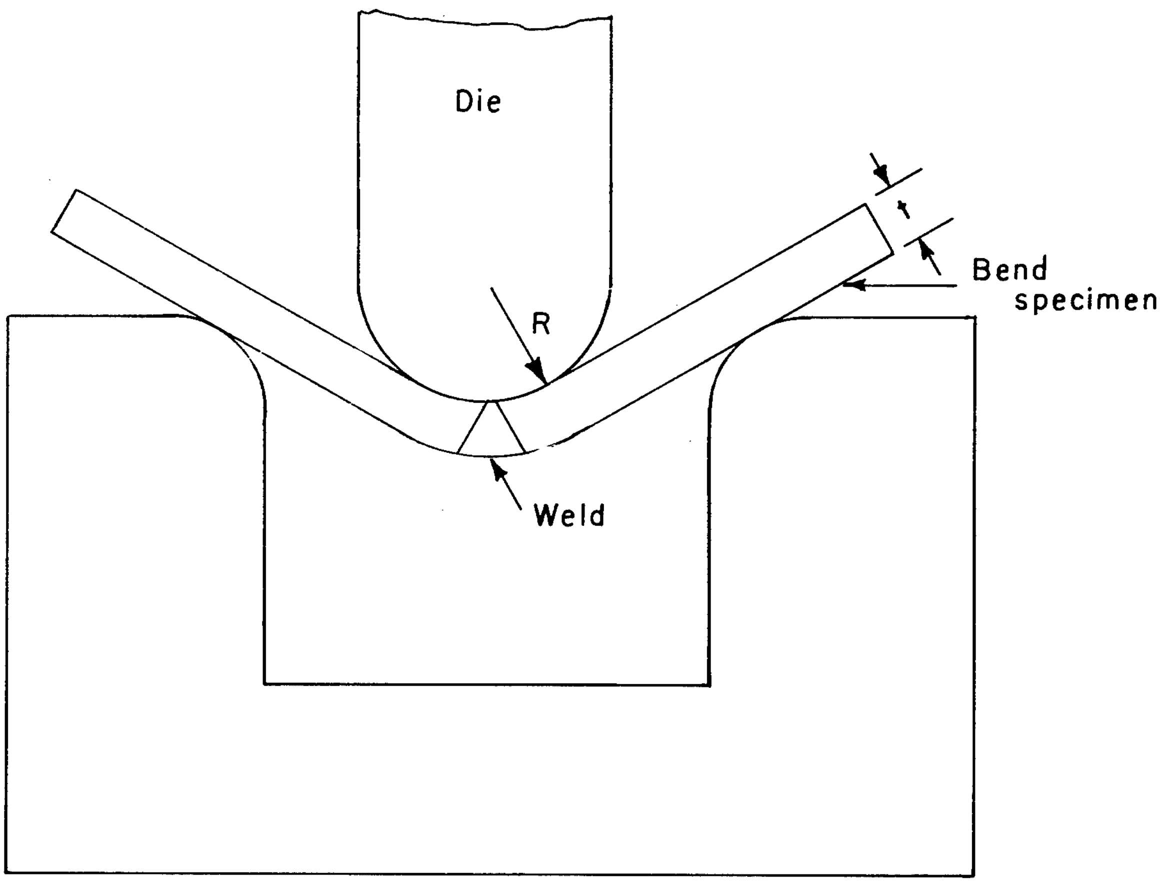


FIGURE 116. SCHEMATIC REPRESENTATION OF THE BEND TEST NORMALLY USED FOR WELD-PROCEDURE QUALIFICATION (Weld is oriented for face bend test)

(5) Nick-break tests are required in some welding codes to detect weld defects. The nick-break test specimen is similar to a rectangular tensile-test specimen, except that notches are cut at the center of the weld. The specimen is then broken by either pulling it in tension or by bending it. The specimen is forced to break in the weld metal because of the notches. After the specimen has been broken, the fracture surfaces are examined for presence of weld-metal defects. If the defects exceed the allowable minimum, the weld is rejected.

(6) Various types of impact tests are sometimes used to test the fracture toughness of the weld metal when low-alloy, high-strength steels are being welded. These tests are designed to measure the ability of the weld metal to resist crack propagation under conditions of low stress.

(7) Metallographic examination of weld sections may be required for certain applications, particularly when the configuration of the weld does not lend itself to the obtaining of meaningful test results by the normal mechanical-property test methods discussed above. Sections of the weld are polished and etched and examined under low magnification to detect porosity, cracks, or other defects in the weld metal.

d. Usefulness of Procedure Qualification. The procedure-qualification test is useful for demonstrating the quality and properties of the weld prior to actual production. It is, however, made on a small test plate under simulated production welding conditions. It is practically impossible to duplicate production-welding conditions when the procedure plate is being made. Situations will arise that could not have been anticipated when the procedure was being qualified. Close supervision must therefore be exercised to recognize factors occurring in the production phase that were not considered during procedure qualification. If these factors could alter the quality of the weld, they should be evaluated.

260. PERSONNEL QUALIFICATION

a. Purpose. The personnel-qualification test requires the welder or welding operator to demonstrate that he can produce sound welds by the qualified welding procedure.

b. Method. In personnel-qualification tests, as in procedure-qualification tests, the welder is required to weld a small test plate in a material which is the same or similar to that of the actual production weldment using the procedure qualified for that weldment. This test plate is then tested nondestructively and destructively to assure that the weld soundness meets the minimum acceptance standards required by the welding code governing the particular application.

c. Testing. The testing methods used for personnel-qualification tests usually include the nondestructive tests applicable to the job and bend tests. In some cases, nick-break tests may also be used. These test methods are selected because of their emphasis on weld soundness rather than weld properties. For example, tensile tests are usually not required for personnel qualification.

d. Usefulness of Personnel Qualification. The personnel-qualification test assures a customer, such as the Government, that the welder can produce acceptable welds by the specified procedure that is to be used on the actual weldment. It does not guarantee that the welder will produce satisfactory welds every time, but it does tend to eliminate welders who cannot produce acceptable welds. As in the case of procedure-qualification tests, the value of the personnel-qualification tests increases when the production-welding conditions are simulated as closely as possible. For example, conditions of accessiblity, weather (if the application requires field welding), and welding position should be considered when welding the personnel-qualification tests.

Section III. WELD IMPERFECTIONS.

261. DEFINITION

a. In the broad sense, weld imperfections are separations in the normal metal structure. The separations may result from a parting of the metal such as in the formation of cracks or pores. Alternatively, the separation may have existed from the time the metal was deposited, such as in the case of slag, lack of fusion, and lack of penetration.

b. Weld imperfections may vary widely in size and form. They may be small, atom-sized dislocations that cannot be seen even with the most powerful optical microscope, or they may be major discontinuities visible to the naked eye. They may be in the form of spherical voids, such as in porosity; elongated voids with rounded contours, such as in slag; or elongated voids with very sharp edges, such as cracks and some types of lack of fusion. They may also be merely imperfections in contour on the surface of the weld.

c. For the purposes of this volume, weld imperfections are classified in two categories: flaws and defects. A flaw is defined as a weld imperfection that is not harmful to the service performance of the part. A defect, on the other hand, is defined as a weld imperfection that is harmful to the service performance of the part.

262. COMMON WELD IMPERFECTIONS

a. Porosity. Porosity is defined as the existence of gas pockets or voids in the weld metal. It is usually caused by evolution of gas either from the molten weld metal or from foreign substances entrapped in the weld metal. If these gases cannot escape from the weld puddle before solidification, the weld will be porous. Porosity is also believed to occur from mechanical entrapment of atmospheric gases. Pores are usually spherical in shape, although they may also occur as nonspherical pockets along grain boundaries or as elongated, tubular voids called "wormholes". Large, isolated gas pockets--usually irregular in shape--are sometimes called "blowholes". Porosity may occur anywhere in the weld metal. Most welds will contain some amount of porosity, and, depending on the size and frequency of pores, they may or may not constitute a defect; i.e., a harmful weld imperfection.

b. Cracks.

(1) General. Cracks are linear defects or ruptures caused by stresses in the material. Stresses produced in welding can cause the following types of weld-metal or base-metal cracks:

(a) Hot cracks

(b) Cold cracks

(c) Microfissures.

Cracks may be either longitudinal (in the direction of the weld) or transverse (across or perpendicular to the weld). Crater cracks may be a combination of both types, as shown in Figure 117. According to most welding standards, any weld cracks are considered rejectable defects.

(2) Hot Cracks. Hot cracking occurs at elevated temperatures in the early stages of weld-metal solidification. Normally, hot cracking is related to hot shortness, or lack of strength

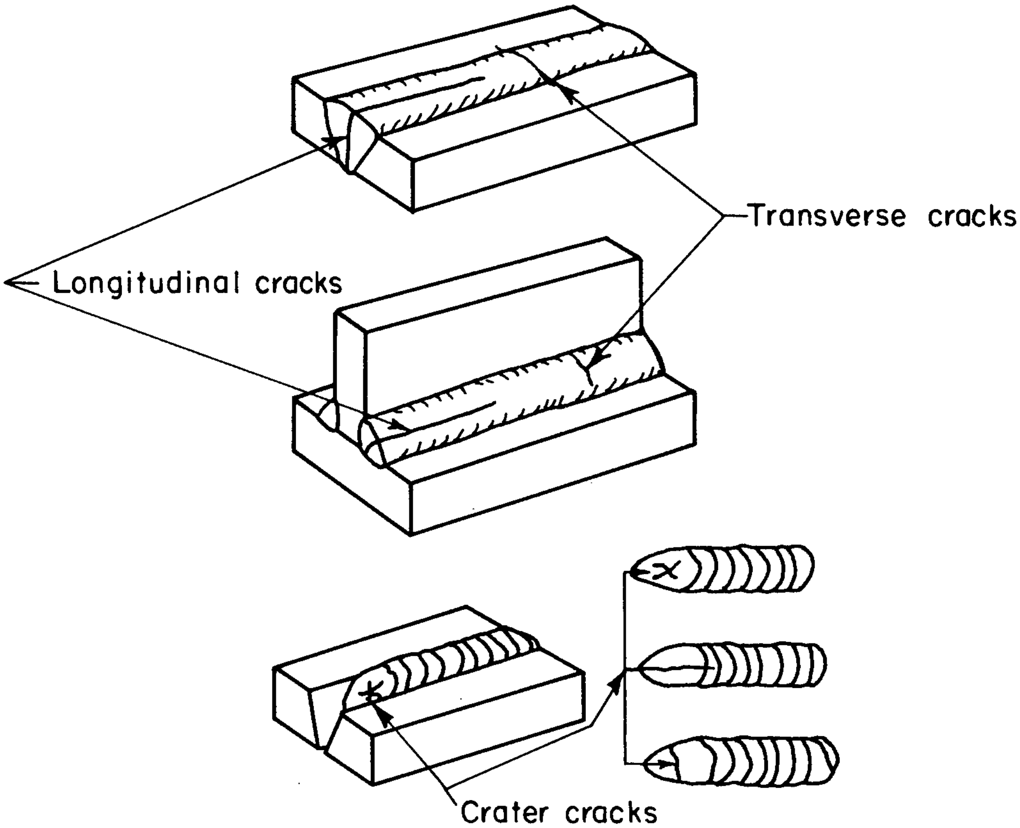


FIGURE 117. TYPES OF WELD-METAL CRACKS

at elevated temperatures. Both metallurgical and mechanical factors contribute to hot cracking. The main metallurgical factors are brittle grain boundaries and intergranular phases that have low melting points. Mechanical factors include joint design, shape and thickness of the weldment, and size and shape of the weld bead. In general, cracking increases as stresses imposed on the weld during solidification increase. Hot cracks are usually centerline cracks, or longitudinal cracks near the fusion line where the most mixing of weld and base metal occurs. In the base metal, hot cracks caused by welding are usually found in the heat-affected zone. With time, these cracks may spread into the weld metal.

(3) Cold Cracks. In steels, cold cracking occurs at temperatures below 400 F and more often at or near room temperature. It may occur hours, or even days, after the weldment has equalized in temperature and is free of thermal stresses.

Cold cracks generally start in the heat-affected zone just under the weld bead, unless the weld metal is harder than the base metal. These cracks run parallel to the weld and are called either toe cracks or underbead cracks. The former occur near the cap pass, the latter near the root of the weld. Cold cracking in steel is primarily associated with the formation of a brittle phase (martensite) or with hydrogen embrittlement. Most cold cracks are found in the base-metal heat-affected zone because in most cases the weld metal is more ductile than the heat-affected zone.

(4) Microfissures. Microcracks or microfissures are cracks so small that they cannot be seen with magnifications of less than ten diameters. Small microfissures are probably present in most base and weld metals. They may be caused by either hot or cold cracking. They are generally intergranular if they are caused by hot cracking and transgranular, but possibly intergranular if they are caused by cold cracking. Microfissures cannot be detected by normal inspection methods.

c. Incomplete Fusion. Incomplete fusion or lack of fusion occurs when some portion of the weld metal is not completely fused with the base metal or previously deposited weld metal. This commonly occurs when the arc is not hot enough to melt the base metal or if the weld metal runs ahead of the arc and cold casts into the joint without melting and fusing to the base metal. Incomplete fusion is commonly found between the weld metal and base metal along the sides of the first or second pass in a joint where the joint is tightest and where it is most difficult to properly direct the arc (see Figure 118). It can occur, however, anywhere in the weld metal. The defect is usually elongated in the direction of welding and may have either rounded or sharp edges, depending on how it is formed.

d. Lack of Penetration. Lack of penetration, incomplete penetration, or inadequate joint penetration occurs when the joint penetration is less than that specified. In full-penetration welds, the joint is to be completely fused. Presence of an unfused joint surface at the root of the joint constitutes a lack-of-penetration defect. In partial-penetration joints, the groove is to be completely fused. If the weld has not penetrated to the bottom of the groove, the void constitutes a lack-of-penetration defect, as shown in Figure 118.

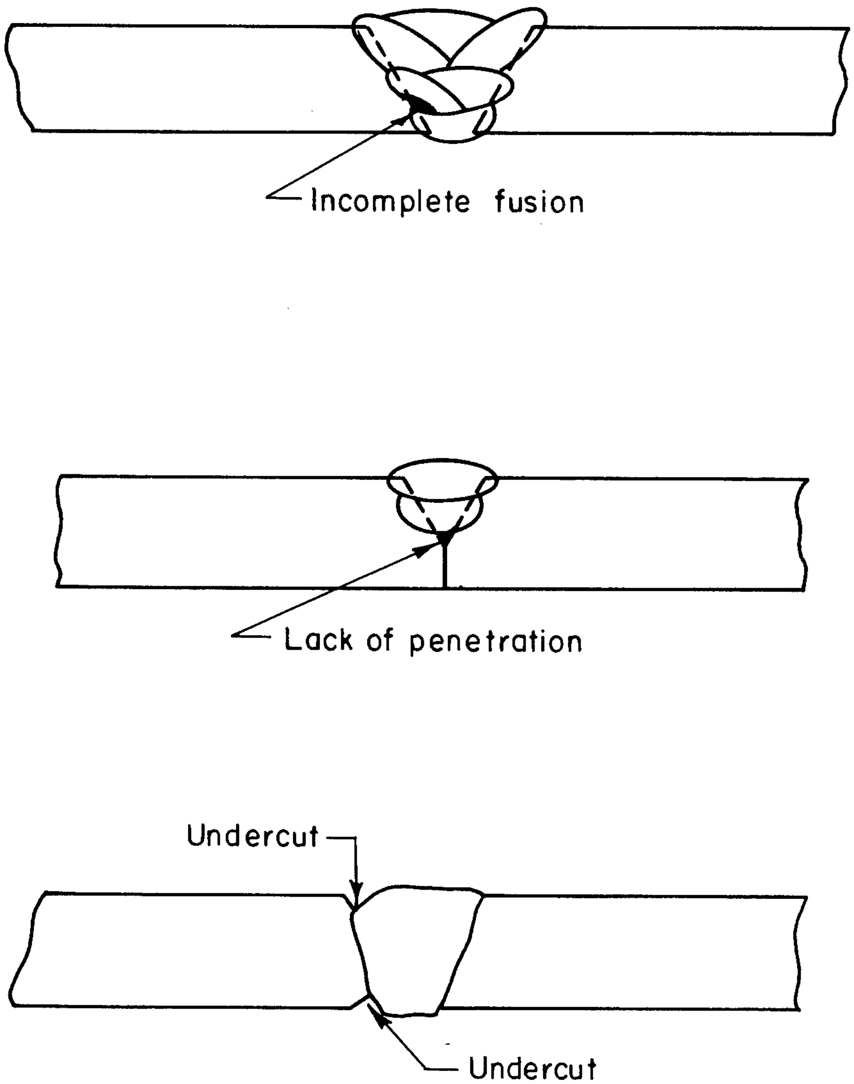


FIGURE 118. DEFECTS COMMONLY FOUND IN ARC WELDS

e. Slag Inclusions. Slag inclusions are nonmetallic, solid material entrapped between weld-metal passes or between the weld metal and the base metal. Slag is produced in the welding process either by the decomposition of welding fluxes or by reactions of alloying elements in the weld with oxygen. Slag may become entrapped when it collects in crevices on the surface of the weld and is not fused out during subsequent weld passes. It is generally linear in the direction of welding and may occur as short particles similar to porosity or as long bands similar to incomplete fusion.

f. Burnthrough. Burnthrough is a void or open hole extending through the bottom of the weld joint. It is caused by local overheating of a spot in the bottom of the joint during deposition of the first or second weld pass. When this spot becomes molten, the metal runs out of the joint, leaving a hole or window in the bottom of the joint. Alternatively, the molten metal may not run out of the joint, leaving a hole. It may merely sag and form icicles on the bottom of the joint; this condition is sometimes called "melt through" or "icicles". In the case of joints welded against a backing strip, complete melting through of the strip in a local area is also called melt through whether the metal sags to form icicles or whether it stays essentially in place. Burnthrough or melt through can occur only in welds deposited from one side of the plate.

g. Undercut. Undercut is a groove melted into the base metal adjacent to the toe or root of a weld and left unfilled by weld metal, as shown in Figure 118. Undercut is a linear surface imperfection that may vary in depth, width, and sharpness at the root of the notch. Since it is a surface defect, it can be readily detected by visual inspection and can be easily repaired, provided the surface is accessible. When it occurs on an inside surface that is inaccessible, such as a small-diameter pipe, it is a much more troublesome condition because the weld must be completely removed and rewelded to remove the defect.

263. OTHER WELD IMPERFECTIONS

a. The weld imperfections discussed in the preceding paragraphs are the common types of imperfections which can occur in most types of arc welds. There are many other types of weld imperfections which are peculiar to certain types of joint designs, materials, or welding processes.

b. In joints made using a backing ring, excessive spacing of the ring from the bottom of the joint is often considered a weld imperfection.

c. Loss of shielding on the root side of the joint, incomplete fusion of the insert, and shrinkage cavities on the inside weld surface caused by rapid withdrawal of the welding arc are types of weld imperfections peculiar to joints welded with consumable inserts.

d. When certain high-nickel alloys are being welded, the grain orientation in the root pass can cause a dark linear indication in X-rays that is often erroneously interpreted as a weld imperfection.

e. The entrapment in the weld of particles of the refractory oxide present on the surface of aluminum alloys can cause imperfections called dross or oxides, which are peculiar to these types of alloys.

Section IV. PREWELD QUALITY ASSURANCE

264. REQUIREMENTS

a. Every step in producing a weldment is directed toward obtaining a product that will meet the minimum requirements established for that product. It is necessary, then, to prevent the formation of harmful defects in the weld. It is always possible, however, that defects will unavoidably or accidentally occur. When this happens, it is necessary to have means of detecting them.

b. Two steps which may be taken prior to welding to reduce the probability of weld defects are procedure-qualification and personnel-qualification tests. These tests demonstrate that the equipment, procedure, and welding operator are capable of producing welds meeting minimum quality requirements. These qualification tests were discussed in Section II of this chapter. The production of a weldment may be required under conditions somewhat different from those encountered in qualification tests, and steps must be taken to provide the best possible conditions for welding.

265. BASE-MATERIAL REQUIREMENTS

a. The surfaces of the base material should be free from oil, grease, and other foreign matter, and should be as free as possible from protective coatings and excessive oxides. Welding should not be carried out when ice, snow, or water is present on the surfaces of the material. Field welding should not be done when it is likely that the quality of the completed weld would be impaired by the prevailing weather conditions, such as airborne moisture or high wind.

b. The joint faces of materials should be visually inspected to be sure that they are free of large laminations and other base-metal defects. If a joint is prepared by flame cutting, its surface should be free of deep gouges. If such gouges are present, they should be filled in by welding before the joint is fitted up. The joint dimensions should be checked to be sure they are within tolerances that can be reliably welded by the qualified procedure.

c. The ability of the base material to withstand the heat of welding is of importance also. Some materials require no special precautions during welding. Others require preheat, special welding procedures, or postweld heat treatment for adequate properties to be developed in the weld joint. Many structural materials now in use were developed for use in welded construction and therefore are highly weldable.

266. ELECTRODE REQUIREMENTS

a. Just as base materials must be capable of withstanding the heat of welding, welding electrodes must be capable of depositing sound welds with good properties. This requirement also holds true for the filler materials for welding processes where the filler is not the electrode.

b. Covered Electrodes.

(1) Shielded-metal-arc welding and the role of the coating on a covered electrode were discussed in Chapter 4. There are no specifications for the composition of coatings for covered electrodes. There are, however, many other requirements that the electrodes must meet.

(2) The coating on the electrode must be concentric in order to provide adequate and constant shielding for the welding arc. For the same reason, the coating must be uniform along the entire length of the electrode. The coverings of the electrodes must be free of surface defects, such as scabs, blisters, cracks, pockmarks, and bruises that would be detrimental to the performance of the electrode. The slag produced by the electrode must be easily removable after welding to prevent its entrapment in subsequent weld passes.

(3) For many applications, the electrodes must pass a qualification test for usability. In these tests, the electrodes are used to deposit a groove weld under controlled conditions.

This weld is subsequently examined radiographically for soundness. If found to be sound, tensile tests are prepared from the weld to demonstrate its strength and ductility properties. Certain classes of electrodes are required to exhibit a certain metal-deposition rate and ratio of metal deposited to core wire consumed. Fillet welds deposited with the electrodes must have good surface appearance and adequate penetration characteristics.

(4) Chemical-composition requirements must also be met by most electrodes. Low-strength, mild-steel electrodes generally do not have composition requirements. Most higher-strength-steel electrodes, electrodes for welding corrosion-resistant materials, and electrodes for welding nonferrous materials do have composition requirements.

(5) The electrodes must be packed for shipment in a manner that will ensure safe delivery and acceptance at their destination. The packages in which the electrodes are shipped are generally marked with the type and classification of the electrodes, the size of the electrode, the weight of the package, and the Government or industrial specification to which the electrode was manufactured.

c. Low-Hydrogen Covered Electrodes.

(1) The effect of large amounts of hydrogen on the weld was discussed in Paragraph 15c. To eliminate as much of the hydrogen from the arc atmosphere as possible, certain groups of electrodes for shielded metal-arc welding are produced from special coating ingredients. These ingredients have very low water content and therefore supply very little hydrogen to the arc. Low-hydrogen covered electrodes require special attention to ensure that no water is absorbed by them during shipping or storage.

(2) After manufacture, low-hydrogen covered electrodes are sealed in airtight containers for shipping. After the containers are opened and the electrodes have been exposed to the air, the electrodes should be stored in an "oven" at 250 F to 350 F. Welding personnel should not be permitted to remove more electrodes from the oven than can be used in 4 hours. If the electrodes are exposed for more than 4 hours,

or there is other reason to believe that the coatings may contain moisture, they can be restored to the low-hydrogen condition by baking at 800 F for 1 hour. The electrodes should then be stored in the oven.

d. Bare Electrodes. Bare electrodes must meet chemical, mechanical-property, and usability requirements similar to those for the covered electrodes. In addition, the wire should have an extra-clean, smooth, and bright finish free of bends, breaks, seams, and other objectionable defects that would have a harmful effect on the weld quality, or which would interfere with smooth, continuous feeding through the welding equipment. Copper or other suitable coatings may be used on some electrodes for welding mild steel to prevent corrosion of the electrode surface and to improve electrical contact in the welding torch.

267. GAS-SHIELDING REQUIREMENTS

Shielding gases for welding should be of high purity and should have low moisture content. Argon should typically be a minimum 99.95 percent pure and have a dew point of minus 65 F or colder. Carbon dioxide should be designated as welding grade.

Section V. IN-PROCESS QUALITY ASSURANCE

268. REQUIREMENTS

a. General. The steps taken during the welding of a structure are at least as important in producing a quality weldment as those taken prior to welding. These steps are all aimed at preventing the formation of weld defects.

b. Equipment Care.

(1) Equipment in good working condition is necessary for the production of quality welds. Care of the equipment is not spelled out in most welding procedures, but is implied in the procedure qualification.

(2) The working portions of a power supply should be kept reasonably free of dust and dirt and should be kept well lubricated. A minimum of maintenance of this type will ensure the continued good performance of the machine. All cooling-water and gas-shielding connections should be kept

tight. Leakage of water into the shielding gas or into the arc region is a source of hydrogen and oxygen to the molten metal. Loose gas connections can allow air leakages into the gas line, again putting impurities into the region of the molten metal.

(3) The electrode holder and current-carrying leads for shielded metal-arc welding should be kept in good condition. Broken electrode holders and split insulation on leads are not only safety hazards, but may short out, causing a weld defect. The welder's face shield should be kept clean to ensure continued good visibility.

c. Welding Procedures. The importance of procedure qualification was discussed in Paragraph 259. These qualifications are used to show that sound welds with good properties can be made by the procedures developed for making these welds. If continued production of high-quality welds is to be achieved, these procedures must be followed when the actual weldment is being produced.

d. Preheat and Interpass Temperature.

(1) The importance and effect of preheat were discussed in Chapter II. It is necessary to use the proper preheat temperature for the materials being welded. The same is true for interpass temperatures; i.e., the temperature maintained in the weld between weld passes.

(2) The preheat temperatures vary with material types and sometimes with thicknesses. Mild steels generally require very little or no preheat, but in general should not be welded when the temperature of the material is lower than approximately 60 F. Some low-alloy steels require only low preheat to approximately 100 F. Castings or highly hardenable steels, on the other hand, may require preheats of 500 F and higher.

(3) While steels are preheated to reduce the formation of very hard zones in the material, other materials are preheated for different reasons. Copper or aluminum, for example, may be preheated to reduce the rate at which heat is removed from the weld area. This greatly aids the formation of a weld pool and reduces the chance of incomplete fusion in the weld.

(4) Control of maximum interpass temperature is also very important. Limits on interpass temperature are imposed on different materials for many different reasons. All of these reasons usually pertain to obtaining optimum mechanical or physical properties in the weld heat-affected zones. For example, the interpass temperature on some stainless steels is controlled to protect the corrosion resistance of the material. The interpass temperature on low-alloy steels is limited in many cases to assure good fracture toughness in the heat-affected zone. In high-nickel alloys, the interpass temperature is often limited to prevent microcracks in the heat-affected zone. The minimum interpass temperature, of course, should be the preheat temperature of the material.

Section VI. POSTWELD QUALITY ASSURANCE

269. GENERAL

a. Postweld quality assurance consists mainly of conducting the necessary nondestructive tests on the weld to assure that the weld meets the acceptance standards required for its intended application. These tests are intended primarily to check for physical defects in the weld metal and heat-affected zones. The properties of the joint are assumed to be satisfactory, based on the fact that the welds were made with proper materials and procedures that were previously qualified as producing satisfactory weld properties.

b. It is generally desirable to inspect a single weld or several welds in a part as soon as they are completed, before other parts are added to the weldment that would complicate making repairs. The extent to which this general rule is followed depends on the type of part and the economic consideration of simplifying repairs versus increasing costs through additional nondestructive testing stages.

c. Postweld inspection is not a substitute for supervision of the welding operations or for proper welding procedures, welding equipment, and materials. The purpose of this inspection is to assure that all of the requirements applicable to a job have been followed and that the resultant welds are as specified on design drawings and in job specifications.

d. Properly performed, postweld inspection is reasonable in cost and can contribute to cost savings by finding defects when they can be readily repaired and by eliminating the necessity to scrap parts.

e. Virtually every inspection method available has been used for the examination of welds, including visual inspection, magnetic-particle inspection, dye-penetrant inspection, eddy-current inspection, ultrasonic inspection, and radiography using X-rays and isotopes. The method and the extent of the inspection will vary with the nature of the work and the criticality of certain joints. Some factors that should be considered in selecting nondestructive tests for weldments are:

(1) Material to be tested

(2) Joining process

(3) Geometry of material

(4) Defects possible or expected

(5) Sensitivity and resolution desired or required.

270. VISUAL INSPECTION

a. Visual inspection is probably the most widely used inspection method. It is simple, inexpensive, and the only equipment commonly used is a magnifying glass (X 10 or less). Despite the many factors that are beyond the scope of visual examination, it must be regarded as one of the most important methods for determining weld quality. A great deal can be learned from the surface condition of a welded joint, and careful evaluation of the appearance, the structure, and similar factors can contribute much toward the determination of final acceptability. This is particularly true when the information is used in conjunction with other inspection methods.

b. Visual examination is usually the first stage in the inspection of a finished weld. The following quality factors can usually be determined by this means:

(1) Dimensional accuracy of the weldment (including warpage)

(2) Conformity to specification requirements regarding the extent, distribution, size, contour and continuity of welds

(3) Weld appearance

(4) Surface flaws, such as cracks, porosity, unfilled craters and crater cracks, particularly at the ends of welds, undercutting, etc.

c. The objective of all inspection methods is to reveal any flaws or defects in a part that may affect service performance. Accordingly, inspection should be preceded by adequate cleaning to remove slag, oxide films, etc. Care should be taken when any cleaning method such as shot-blasting is used. Fine cracks and similar imperfections may be sealed on the surface and rendered invisible to visual inspection.

d. Correct interpretation and evaluation of discrepancies in the appearance of welds are essential in visual inspection. A sound knowledge is necessary, therefore, of the welding process involved and the service requirements, together with the experience and judgment needed to evaluate the quality of a weld by visual inspection.

271. RADIOGRAPHY

a. Radiography is a nondestructive test method that shows the presence and nature of macroscopic defects or other discontinuities in the interior of welds.

b. This test method makes use of the ability of short-wavelength radiations, such as X-rays or gamma rays, to penetrate objects opaque to ordinary light. In general, the shorter the wavelength, the greater the penetrating power.

c. Not all of the radiation penetrates the weld, some being absorbed. The amount of this absorption is a function of the density and the thickness of the weld. Should there be a cavity, such as a blowhole in the weld interior, the beam of radiation will have less metal to pass through than in a sound weld. Consequently, there will be a variation in the absorption of the rays by the weld in the defective region. These variations, if measured or recorded on a film sensitive to the radiation, produce an image that will indicate the presence of the defect, as shown in Figure 119. Such an image picture is called a radiograph.

d. A number of types of defects common to welding may easily be shown by means of radiography. Slag inclusions, as shown on a radiograph, are usually of irregular shape. The images of porosity or gas pockets usually appear as small dark spots. The images may be fine or coarse, and they may be widely scattered or closely grouped. Cracks in

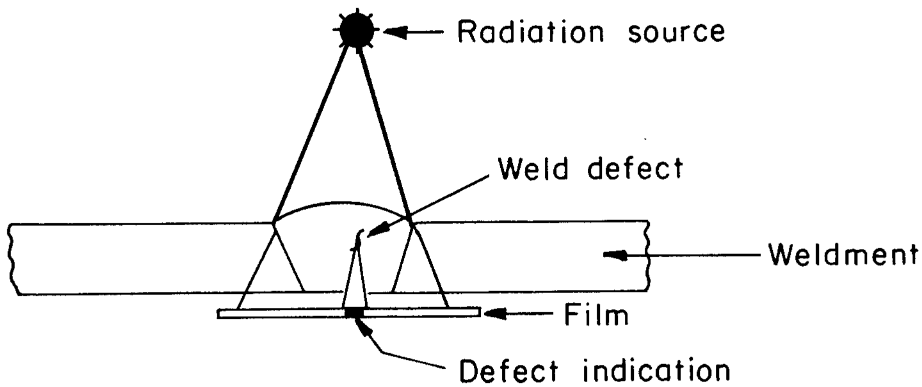


FIGURE 119. SCHEMATIC REPRESENTATION OF THE DETECTION OF WELD DEFECTS BY RADIOGRAPHY

welds produce film images of a line darker than the film background. Because they extend primarily in one plane, some of them require special techniques to produce a satisfactory image on the film. This is particularly true when the plane in which they lie is not perpendicular to the X-ray beam.

e. Other defects common to welding may also be shown by radiography, including inadequate penetration, undercut, surface defects, and incomplete fusion. The inspector's ability to recognize these according to type is largely a matter of his experience and his acquaintance with standards. The limits of acceptability are defined in applicable codes and specifications.

272. MAGNETIC-PARTICLE INSPECTION

a. Magnetic-particle inspection is a nondestructive method of detecting cracks, seams, inclusions, segregations, porosity, lack of fusion, and similar discontinuities in magnetic materials. It is not applicable to nonmagnetic materials. This method will detect surface discontinuities that are too fine to be seen with the naked eye, those that lie slightly below the surface and, when special equipment is used, the more deeply seated discontinuities.

b. The principle of magnetic-particle inspection involves the minute poles that are set up at discontinuities when a magnetic field is established in a piece of ferromagnetic material that contains one or more discontinuities in the patch of the magnetic flux. These poles have a stronger attraction for the magnetic particles than the surrounding surface of the material.

c. The piece to be inspected is magnetized by introducing high-amperage current by putting the piece in a coil, or by some other convenient means. The magnetic field in the part is interrupted by discontinuities, and a leakage field is produced on the surface. The areas to be inspected are covered by finely divided magnetic particles, which react to the magnetic leakage field produced by the discontinuity. These magnetic particles form a pattern or indication on the surface that assumes the approximate shape of the discontinuity, as shown in Figure 120.

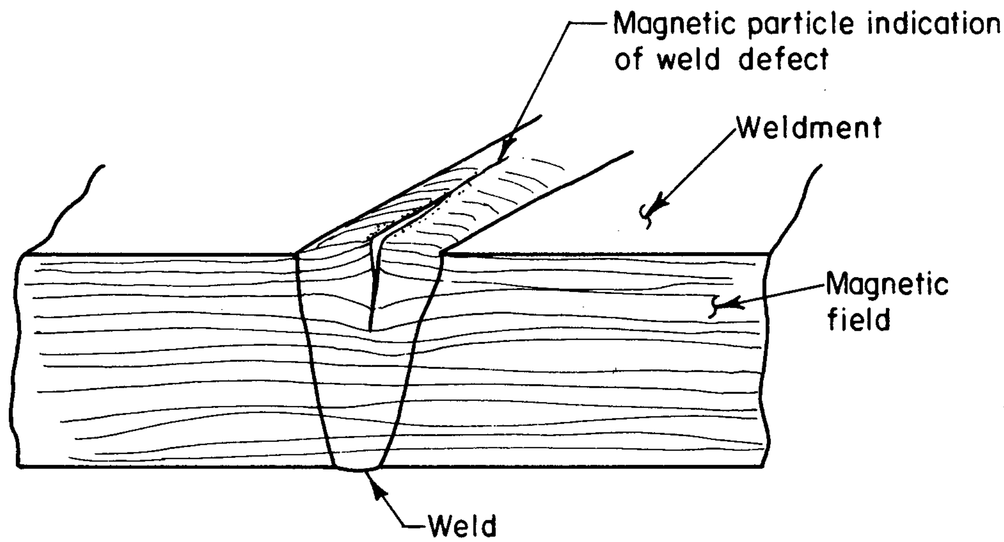


FIGURE 120. METHOD OF DETECTION OF WELD DEFECTS BY MAGNETIC-PARTICLE INSPECTION

d. The magnetic-particle method of inspection may be used to inspect welds and plate edges prior to welding, and to inspect welded repairs. Among the defects that may be detected are: surface cracks of all kinds, both in the weld and in the adjacent base metal; laminations or other defects on the prepared edge of the base metal; incomplete fusion and undercut; subsurface cracks; and inadequate penetration at the root.

e. The magnetic method of inspection is applicable only to ferromagnetic materials in which the deposited weld metal is also ferromagnetic. It cannot be used to inspect nonferrous materials or the austenitic steels. Difficulties may arise during inspection of weldments in which the magnetic characteristics of the deposited metal are appreciably

different from those of the base metal. Joints between metals of dissimilar magnetic characteristics create magnetic discontinuities that may produce indications even though the joints themselves are sound. Subsurface porosity and slag inclusions produce powder patterns that are not clearly defined.

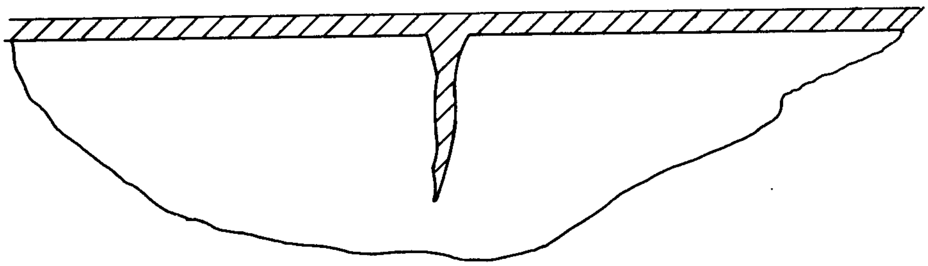
f. The degree of sensitivity in this method depends upon certain factors. Sensitivity decreases with a decrease in size of the discontinuity and also with an increase in depth below the surface. A decrease in sensitivity is evident when discontinuities are rounded or spherical rather than long and crack-like. Maximum sensitivity is obtained when defects are essentially normal to the surface inspected.

g. A discontinuity must sufficiently interrupt or distort the magnetic field to cause external leakage. Fine elongated discontinuities, such as seams, inclusions, or fine cracks, will not interrupt a magnetic field that is parallel to the direction of the discontinuity. In this case, no indication of them will be apparent. Such discontinuities can, however, be detected by using a magnetic field that is not parallel to the discontinuity. If the general direction of possible defects is unknown, it is necessary to perform magnetic-particle inspection by magnetizing from two directions.

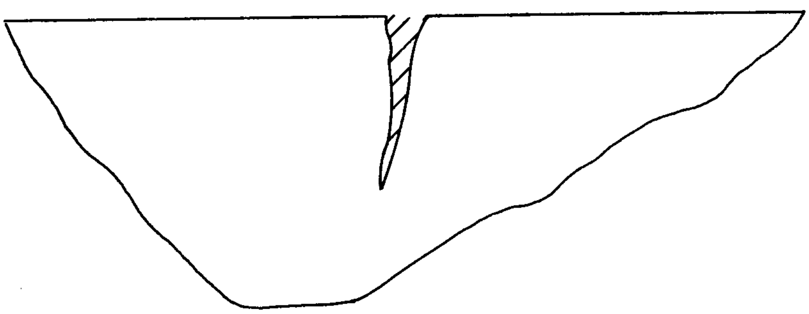
h. The surface conditions also influence the sensitivity of the inspection process. The surface should be clean, dry, and free from oil, water, excessive slag, or other accumulations that would interfere with efficient inspection. Wire brushing, sandblasting, or other comparable cleaning methods are usually satisfactory for most welds. Surface roughness decreases the sensitivity and tends to distort the magnetic field. It also interferes mechanically with the formation of powder patterns.

273. PENETRANT INSPECTION

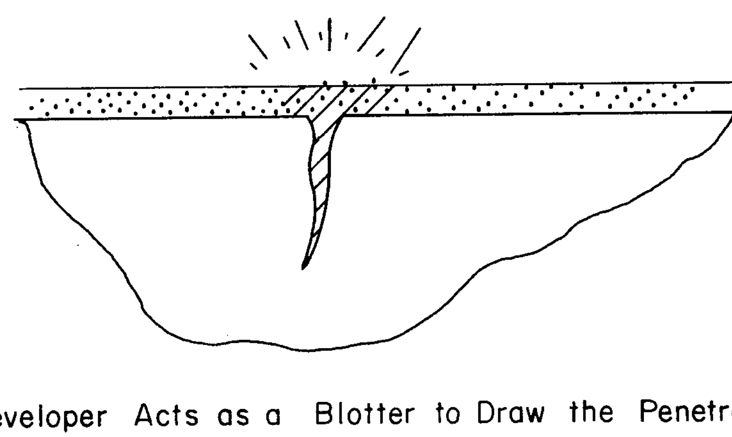
a. Penetrant inspection is a sensitive, nondestructive method of detecting and locating minute discontinuities, such as cracks, pores, and leaks, which are open to the surface. It is particularly useful on nonmagnetic materials where magnetic-particle inspection cannot be used. In the welding field it is used extensively for exposing surface defects in aluminum, magnesium, and austenitic-steel weldments, and for locating leaks in all types of welds. The ability to recognize visual indications is the determining factor and the efficiency of the method depends upon the correct evaluation being placed upon these indications. The basic steps in penetrant inspection are shown in Figure 121.



a. Seepage of Penetrant into Defect Open to Surface of Part



b. Penetrant Removed from Surface of Part but not from Defect



c. Developer Acts as a Blotter to Draw the Penetrant from the Defect and Produce an Indication

FIGURE 121. BASIC STEPS IN PENETRANT INSPECTION OF A WELD

b. Fluorescent-penetrant inspection makes use of a highly fluorescent liquid with unusual penetrating qualities. It is applied to the surface of the part to be inspected and is drawn into extremely small surface openings by capillary action. After sufficient penetration time has been allowed, the excess is removed from the surface without removing it from the defects being sought. A developer is then applied, which draws penetrant from the defect and which produces fluorescence visible under black light. The high contrast of the fluorescence makes it possible to detect minute indications easily.

c. Dye-penetrant inspection is essentially similar in materials and techniques to fluorescent-penetrant inspection, except that it makes use of visible instead of fluorescent dyes in the penetrant, and the indications are observed under normal, white light. It is particularly useful when portability is a factor to consider, or where the use of black light is impractical.

d. Dye-penetrant inspection is a three-stage operation. The part is sprayed with a cleaner to remove all oil, grease, and foreign materials. It is then sprayed with the dye-penetrant, which penetrates surface cracks and irregularities. The excess penetrant is removed. Finally, the part is sprayed with the developer. This may be a chalky substance that dries on contact. The substance is stained by the dye, which rises by capillary action from flaws in the surface and marks them clearly in red.

e. Penetrant inspection is applicable equally to both large and small weldments. Pressure and storage vessels and piping in the petroleum, chemical, and dairy industries are often made of nonmagnetic materials and may be inspected for surface cracks and porosity by this method. Small aluminum, magnesium and austenitic steel weldments for such applications as aircraft, jet engines, and welded valve facings are equally applicable to penetrant-inspection techniques. Penetration inspection may be used for detection of cracks, pores, and leaks through the lining in lined or clad vessels of the type used in the petroleum and chemical industries. It may be applied to all types of welded linings. Shallow cracks and porosity may be distinguished from those that extend through the lining (leakers), since the indications of leakers spread rapidly or bleed upon application of dry developer.

274. EDDY-CURRENT INSPECTION

a. Eddy-current testing is a nondestructive test method that makes use of electromagnetic energy to detect discontinuities and metallurgical

variations in metal. It is used to check welds in ferrous and nonferrous products and is particularly useful in testing welded pipes and tubes.

b. It employs one or more coils energized with alternating current. The frequency may vary from 50 cycles to 1 megacycle, depending on type and thickness of material.

c. The part to be inspected may be passed through an encircling coil, or the weld may be scanned by a probe-type coil. Discontinuities in the weld will produce changes in the coil impedance, which is sensed by the associated electronic instrumentation. Signals are indicated by meters, recorders, or oscilloscopes. On automatic equipment, all signals over a predetermined threshold level will cause the weld to be marked. Threshold level is usually determined by specification or by correlation of the electronic signals with other nondestructive or destructive tests and is preferably related directly to the serviceability of the finished product.

d. The sensitivity of this method drops significantly as the depth of the defect increases.

275. ULTRASONIC INSPECTION

a. Ultrasonic inspection is a rapid and efficient, nondestructive method of detecting, locating, and measuring both surface and subsurface defects in the weldment and/or base materials. High-frequency vibrations are more sensitive to fine cracks and subsurface defects than the other common inspection methods. Cracks, small enough to be termed microseparations, may be detected. A basic method of ultrasonic inspection is shown schematically in Figure 122.

b. Ultrasonic inspection may be used to detect flaws in all types of welded joints such as nozzles, branches, manholes, and fillet and structural welds, as well as main welded seams. As only one inspection surface is required, many types of welded joints can be satisfactorily examined. Defects that are either entirely subsurface or are on the opposite or inaccessible surface, such as the bore or root of a pipe weld, can be detected and evaluated.

c. The exact location of a fault can be determined and its size measured. Dimensions such as depth, length and width of any flaw having dimensions can be measured from either surface, even though the flaw is entirely subsurface or is located in the opposite surface.

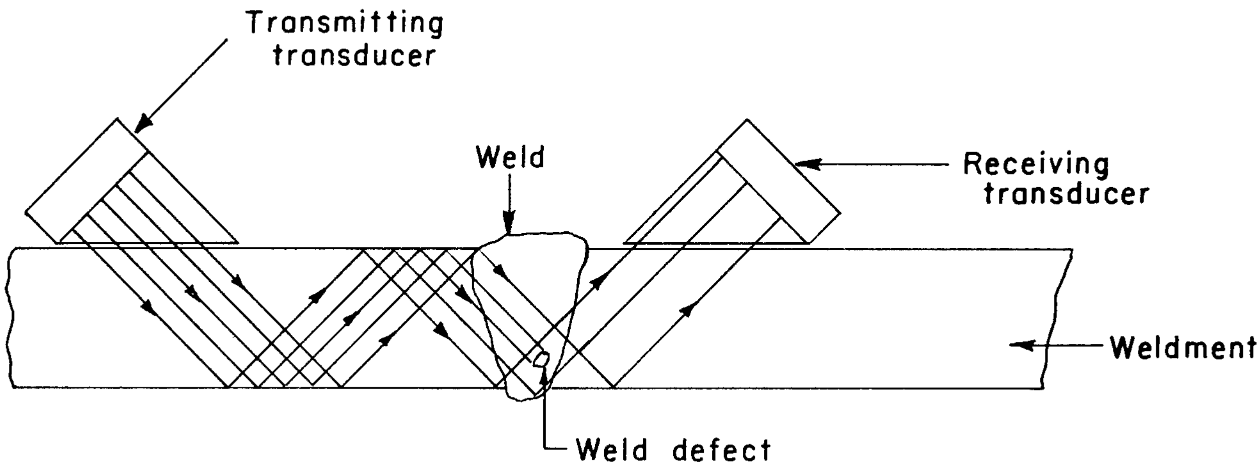


FIGURE 122. TWO-TRANSDUCER METHOD OF ULTRASONIC INSPECTION OF A WELD

276. OTHER TESTING METHODS

a. Removal of samples by sectioning is an accepted method of weld inspection approved by various pressure-vessel codes. While the cavity must later be repaired by rewelding, the method is nevertheless considered a nondestructive test. Samples may be taken for chemical analysis, etch tests, subsize tension tests, or impact tests. The method of removing samples will depend on the size of specimen desired; however, a hole saw, trepanning tool, cold chisel, or boat-cutter--a special power tool with a hemispherical saw--are common tools used for sample removal. The samples must be carefully selected to be representative of the weld or base metal being checked.

b. The practice of subjecting a completed pressure vessel to a test that will produce stress somewhat above the design maximum is a long-established safety measure. The principal objective, aside from the detection of leaks, is to give some assurance of the absence of serious defects in workmanship, materials, and design. The test does not guarantee that the vessel will withstand subsequent applications of the same pressure or that periodic applications of the lower service pressure might not produce failure. For reasonable assurance of safe construction, other inspection for the detection of flaws is essential.

277. APPLICATIONS ON NONDESTRUCTIVE TESTING TO WELDS

a. There is no universal nondestructive testing method that can reliably detect all weld defects. In fact, there is always the statistical probability that a defect may go undetected by even the best nondestructive test.

b. A good weld nondestructive test program makes use of various test methods to detect defects most readily apparent from each. The most commonly used methods of nondestructive testing welds are a combination of visual inspection, magnetic-particle or penetrant inspection and radiography. Eddy-current inspection and ultrasonic testing are commonly used for some high-speed welding processes such as those used on tube or pipe mills.

c. Visual inspection of the weld is the first step in nondestructive testing of the welds. The weld should be inspected to assure that it has adequate size, is properly contoured, and is free of surface imperfections such as undercut and gross cracks or porosity.

d. Magnetic-particle or dye-penetrant tests are used to detect small cracks or lack-of-fusion defects that are open to the surface but too small to detect by visual examination. In magnetic-particle testing, such defects may in some cases be detected when they are below the surface.

e. Radiography has in the past been the acid test for checking weld soundness. It is generally very reliable, when properly performed, in detecting imperfections that are open, i.e., that have a significant volume of different radiographic density than the weld metal. For example, porosity, slag, and open lack of fusion are readily detected. Closed imperfections, such as cracks, are also readily detected if they are aligned with the radiation direction so that the radiation has a sufficiently long path within the imperfection. In this case, the crack will appear as a dark, fairly sharp line on the radiograph. If the crack is slightly misaligned with the beam, it may still be detectable, but it now appears as a broadened band on the X-ray and is not as dark as in the case of the aligned crack. The more the crack is misaligned, the less sharp and lighter the film indication becomes. With only relatively small misalignment, a tight crack may be undetectable.

f. Ultrasonic testing of welds is becoming more and more widely used. Ultrasonic testing has an advantage over radiography because it detects any defect with sufficient reflecting surface whether the defect is open or closed. It is therefore a good method of detecting subsurface

cracks, which are the most serious type of weld defects. Ultrasonic testing, in its present state of development, has several disadvantages compared to radiography. It does not produce a pictorial record of the defect as radiography does. It is often difficult to separate spurious indications caused by reflections from normal geometrical features of the weld, from true defect indications. It is less reliable than radiography in evaluating the extent of porosity (the most common weld flaw) and in deciding whether the porosity meets presently used acceptance levels as described for radiographic tests.

g. Eddy-current tests are very useful for detecting defects open to the surface or just below the surface. It is used quite extensively to inspect welds in thin-wall tubing because the high inspection rates possible with eddy-current tests make it possible for the inspection to keep pace with the high welding speeds.

GLOSSARY OF TERMS USED IN ARC WELDING

ALTERNATING CURRENT - An electric current that reverses its direction at regularly recurring intervals.

ANNEALING - A heat-treating process used to improve ductility of metal. In steel, usually refers to very slow cooling from the austenitizing range.

ANODE - The positive pole in an electric arc.

ARC - A discharge of electricity across a gap in a circuit or between two electrodes.

ARC BLOW - The swerving of an electric arc from its normal path because of magnetic forces.

ARC COLUMN - The region of a welding arc that lies between the anode and cathode.

ARC CURRENT - See welding current.

ARC LENGTH - The distance the welding arc must travel from the electrode to the work.

ARC ROOT - The constricted region of an arc column where it meets the electrode.

ARC VOLTAGE - The voltage across the welding arc.

ARC WELDING - A group of welding processes in which fusion is obtained by heating with an electric arc or arcs, with or without the application of pressure and with or without the use of filler metal.

AUSTENITE - A solid solution in iron of carbon and sometimes other solutes that occurs as a constituent of steel under certain conditions.

AUTOMATIC WELDING - Welding with equipment which performs the entire welding operation without constant observation and adjustment of the controls by an operator. The equipment may or may not perform the loading and unloading of the work.

BACKING OR BACKUP - Material (metal, weld metal, asbestos, carbon, granular flux, etc.) backing up the joint during welding to facilitate obtaining a sound weld at the root.

BACKING STRIP OR BAR - Backing in the form of a strip or bar placed on the bottom side of the weld joint.

BARE ELECTRODE - In arc-welding, a consumable filler-metal electrode made of a metal wire with no coating other than that incidental to the drawing of the wire.

BASE METAL - The metal to be welded.

BEVEL ANGLE - The angle formed between the prepared edge of a member and a plane perpendicular to the surface of the member.

BRAZING - A group of welding processes in which fusion is obtained by heating to suitable temperatures above 800 F but below the melting temperature of the base metal and adding a nonferrous filler metal with a melting point below that of the base metals. The filler metal may be deposited in an open joint between the parts, or may be distributed between closely abutting surfaces of the joint by capillary attraction.

BURN-OFF RATE - The rate at which an arc-welding electrode is consumed during welding. Expressed in weight or length per unit of time.

BURNTHROUGH - Excessive penetration in a weld.

BUTT WELD - A weld between two members lying approximately in the same plane. See Figures 81-87.

CARBON-ARC WELDING - An arc-welding process in which fusion is obtained by heating with an electric arc between a carbon electrode and the work. No shielding is used and pressure and filler metal may or may not be used.

CARBON ELECTRODE - A non-filler-metal electrode used in arc welding, consisting of a carbon or graphite rod.

CATHODE - The negative pole in an electric arc.

CLADDING - See surfacing.

COALESCENCE - A growing together or merging into a single body. A weld.

COATED OR COVERED ELECTRODE - An arc-welding, filler-metal electrode in which a metal core wire is covered with a material which, when melted by the arc, protects the molten weld pool from the atmosphere, improves the properties of the weld and stabilizes the arc.

COLD SHUTS - See Incomplete Fusion.

COMPOSITE ELECTRODE - A filler-metal electrode, used in arc welding, made of two or more metal components combined mechanically.

CONSTANT POTENTIAL - A characteristic of a welding power supply in which the machine output voltage remains nearly constant as the current increases or decreases. Used primarily for gas metal-arc welding.

CONSUMABLE ELECTRODE - An electrode that is consumed in the weld pool and becomes part of the weld metal.

CORNER JOINT - A joint between two members located approximately at right angles to each other in the form of an L. See Figures 81-82, 84-86.

CRATER - A depression at the termination of a weld bead or in the weld pool beneath the electrode.

DEPOSITION RATE - The weight of metal deposited in a unit of time, usually expressed in pounds per hour.

DEPTH OF FUSION - The distance that fusion extends into the base metal from the surface melted during welding.

DIP TRANSFER, OR SHORT-CIRCUITING, WELDING - A gas metal-arc welding process in which metal transfer occurs during repetitive short circuits through contact of the molten electrode with the weld puddle.

DIRECT CURRENT - An electric current flowing in one direction only.

DOUBLE-BEVEL GROOVE WELD - A type of groove weld. See Figure 85.

DOUBLE-J GROOVE WELD - A type of groove weld. See Figure 89.

DOUBLE-U GROOVE WELD - A type of groove weld. See Figure 87.

DOUBLE-VEE GROOVE WELD - A type of groove weld. See Figure 83.

DOWNHAND POSITION - See flat position.

DROOPING CHARACTERISTIC - A characteristic of a welding power supply in which the machine voltage decreases as the current increases. Power supplies of this type provide an almost constant current and are used for manual welding.

DUCTILITY - The capacity of a metal to be drawn or formed.

EDGE JOINT - A joint between the edges of two or more parallel or nearly parallel members. See Figure 81.

ELECTRODE - The conductor by which current is carried to the welding arc. It may also serve other purposes such as providing filler metal and shielding the arc. See also bare electrode, carbon electrode, composite electrode, coated electrode, and metal electrode.

ELECTRODE EXTENSION - The distance between the contact tip and the arc in arc welding. Also called stick-out.

ELECTRODE HOLDER - A device used for mechanically holding the electrode and conducting current to it.

ELECTROGAS WELDING - A fully automatic fusion process used for butt, corner and tee joints on plates set in the vertical position. The plates are spaced apart and welding is performed in a rectangular pocket or cavity formed by water-cooled copper shoes that span the gap between the pieces being welded.

ELECTROMAGNETIC FORCE - In welding, the force due to the interaction of the welding current with its own magnetic field.

ELECTRON - An elementary particle consisting of a charge of negative electricity.

ELECTRON BEAM WELDING - A welding process in which the heat for fusion is obtained from bombardment of the workpiece by a dense stream of high-velocity electrons.

ELECTROSLAG WELDING - An arc welding process that uses a molten slag to melt the filler metal and the surfaces of the metal being welded.

FACE OF WELD - The exposed surface of a weld, made by an arc- or gas-welding process, on the side from which welding was done.

FILLER METAL - Metal to be added in making a weld.

FILLER WIRE - See welding rod.

FILLET WELD - A weld of approximately triangular cross-section joining two surfaces approximately at right angles to each other in a lap joint, tee joint, or corner joint. See Figures 90, 91.

FLAT POSITION - A welding position in which welding is performed from the upper side of the joint with the face of the weld approximately horizontal. See Figures 97, 98.

FLUX - Material used to facilitate removal of, to prevent the formation of, or to dissolve oxides and other undesirable substances.

FLUX-CORED ELECTRODE - Arc-welding, filler-metal electrodes which consist of a hollow tube filled with a mixture of deoxidizers, fluxing agents, metal powders, and ferroalloys.

FLUX-CORE WELDING - A gas-shielded, metal-arc welding process that uses flux-cored electrodes to provide shielding gas, slag-forming materials, deoxidizing agents, and alloy additions.

FORGE WELDING - A group of welding processes in which fusion is obtained by heating in a forge or other furnace and by applying pressure or blows.

FORM FACTOR - The ratio of the total width of the weld pool to its maximum depth.

FUSION - The melting together of filler metal and base metal, or of base metal only, which results in coalescence.

FUSION JOINING - Processes in which the parts to be joined are heated until they melt together.

FUSION ZONE - The area of base metal melted as determined on the cross-section of a weld.

GAS CARBON-ARC WELDING - An arc-welding process in which fusion is obtained by heating with an electric arc between a single carbon electrode and the work. Shielding is obtained from a gas or gas mixture (which may contain an inert gas).

GAS METAL-ARC WELDING - An arc-welding process in which fusion is obtained by heating with an electric arc between a filler metal electrode (consumable) and the work. Shielding is obtained from a gas, a gas mixture (which may contain an inert gas), or a mixture of a gas and a flux. The process is also called Metal Inert-Gas (Mig) welding.

GAS TUNGSTEN-ARC WELDING - An arc-welding process in which fusion is obtained by heating with an electric arc between a single tungsten (nonconsumable) electrode and the work. Shielding is obtained from an inert gas or gas mixture. Pressure and filler metal may or may not be used. The process is also known as Tungsten Inert-Gas (Tig) welding.

GIRTH WELD - A weld that goes completely around the circumference of a body, as in pipe welding.

GLOBULAR TRANSFER - A type of metal transfer in which droplets of molten metal cling to the electrode until they are large enough to drop off due to the force of gravity. The transfer is thus erratic and penetration is shallow.

GROOVE ANGLE - The total included angle of the groove between parts to be joined by a groove weld.

GROOVE FACE - That surface of a member included in the groove.

GROOVE WELD - A weld made in the groove between two members to be joined. See Figures 81 through 89.

HARDNESS - The degree of cohesion of particles on a metal's surface as determined by its resistance to deformation. The hardness of a material is usually measured as its resistance to indentation.

HARD SURFACING - See surfacing.

HEAT-AFFECTED ZONE - The portion of the base metal which has not been melted, but whose mechanical properties or microstructures have been altered by the heat of welding or cutting.

HEAT INPUT - The amount of heat available for welding.

HIGH FREQUENCY - An alternating current that has many thousand cycles per second.

HORIZONTAL FIXED POSITION - In pipe welding, the position of a pipe joint in which the axis of the joint is approximately horizontal and the pipe is not rotated during welding.

HORIZONTAL POSITION - For a fillet weld, a position where welding is performed on the upper side of an approximately horizontal surface against an approximately vertical surface. For a groove weld, a position where the axis of the weld lies in an approximately horizontal plane and the face of the weld lies in an approximately vertical plane. See Figures 97, 98.

HORIZONTAL ROLLED POSITION - In pipe welding, the position of a pipe joint in which welding is performed in the flat position by rotating the pipe.

HOT-WIRE TIG WELDING - A gas tungsten-arc welding process in which the filler wire is preheated to, or near, its melting point as it enters the weld puddle.

INCOMPLETE FUSION - A discontinuity caused by localized temperatures which are insufficient to allow fusion of the molten weld metal and nonmolten weld or base metals.

INCOMPLETE PENETRATION - Joint penetration which is less than that specified.

INERT GAS - Gases that are completely unreactive.

ION - An atom or group of atoms that carries a positive or negative electric charge as a result of having lost or gained one or more electrons.

JOINT OR WELD JOINT - The location where two or more members are joined by welding.

KEYHOLE - An effect in plasma-arc welding in which the arc passes completely through the workpiece forming a hole. The molten metal flows around this hole to form the weld.

LAP JOINT - A joint between two overlapping members. See Figure 91.

LASER - A device which produces a concentrated coherent light beam through the manipulation and control of energy exchanges in solid state transparent media.

LASER WELDING - A welding process which uses the concentrated energy of a focused laser beam to obtain fusion.

LAYER - A stratum of weld metal, consisting of one weld bead or several weld beads lying side by side.

LIQUID SOLID-PHASE JOINING - Those welding processes in which the parts to be joined are heated, but not melted, and a dissimilar molten metal is added to form a solid joint upon cooling. Examples are brazing and soldering.

LOW-HYDROGEN ELECTRODE - Coated electrodes whose coatings are low in hydrogen-forming compounds.

MANUAL WELDING - Welding processes in which the welder holds the electrode holder, guides it along the joint controlling the travel speed, arc length and rate of electrode feed.

MARTENSITE - A very hard, brittle, solid solution of carbon in iron produced by rapidly cooling steel from its austenite range.

MELT-OFF RATE - See burn-off rate.

METAL-ARC WELDING - Any of the arc-welding processes in which fusion is obtained by heating with an arc between a consumable metal electrode and the work.

METAL ELECTRODE - A filler or nonfiller metal electrode, used in arc welding, consisting of a metal wire with or without coating.

METAL TRANSFER - The transfer of filler metal from an electrode or welding rod to the work.

MULTIPASS WELD - Weld in which more than one layer of weld metal is used.

NONTRANSFERRED ARC - In plasma-arc welding, an arc established between the constricting orifice and the center electrode inside the torch.

NORMALIZING - A heat treating process in which nonair-hardening steels are air cooled from the austenitizing range to obtain a fine-grained metal structure.

OPEN-CIRCUIT VOLTAGE - The voltage between the output terminals of the welding machine when no current is flowing in the welding circuit.

OSCILLATION (ELECTRODE) - A lateral movement of the electrode within the joint gap.

OUT-OF-POSITION WELDING - Welding in any position other than the flat position.

OVERHEAD POSITION - The position of welding in which welding is performed from the underside of the joint. See Figures 97, 98.

OVERLAP - Protrusion of weld metal beyond the bond at the toe of a weld.

OVERLAY WELDING - See surfacing.

OXY-ACETYLENE WELDING - A gas-welding process in which fusion is obtained by heating with a gas flame or flames obtained from the combustion of acetylene with oxygen, with or without the application of pressure or the use of filler metal.

PASS - The progression of a welding operation along a joint resulting in a weld bead.

PEARLITE - A mechanical mixture of ferrite and iron carbide resulting from the direct transformation of austenite.

PEENING - The mechanical working of metals by means of hammer blows.

PENETRATION - The minimum depth a groove or flange weld extends from its face into a joint, exclusive of reinforcement.

PINCH EFFECT - A form of metal transfer in which the heated electrode becomes plastic and concentric magnetic forces around it tend to pinch off globules of metal.

PLASMA - A constricted electric arc-gas mixture.

PLASMA-ARC WELDING - An arc-welding process in which fusion is obtained by the heat of a constricted-arc plasma.

PLATE ELECTRODE - An electrode in the form of a plate, rather than a wire, used in electroslag welding.

PLUG WELD - A circular weld made through a hole in one member of a lap or tee joint joining that member to the other. The walls of the hole may or may not be parallel and the hole may be partially or completely filled with weld metal. See Figure 80.

POROSITY - Gas pockets or voids in metal.

POSTHEATING - The application of heat to a weld immediately after the welding operation.

POWER SUPPLY - The source of power for a welding operation.

PRECIPITATION HARDENING - Age hardening carried out at temperatures higher than atmospheric.

PREHEATING - The application of heat to the base metal immediately before a welding operation.

PULSED-ARC WELDING - A gas-shielded arc-welding process that extends spray transfer to lower welding currents by superimposing a high current "pulse" onto a lower background welding current.

REINFORCEMENT - Weld metal on the face of a weld in excess of the metal necessary for the specified weld size.

RESIDUAL STRESS - Stress remaining in a structure or member as a result of thermal or mechanical treatment or both.

RESISTANCE WELDING - A group of welding processes in which fusion is obtained by the heat obtained from resistance of the work to the flow of electric current in a circuit of which the work is a part, and by the application of pressure.

REVERSE POLARITY - The arrangement of direct-current arc welding in which the work is the negative pole and the electrode is the positive pole.

ROOT (JOINT) - That portion of a joint where the members are closest to each other.

ROOT FACE - That portion of the groove face adjacent to the root of the joint.

ROOT OPENING (GAP) - The separation between the members to be joined, at the root of the joint.

ROOT PASS - The welding pass made to lay a bead in the root opening; the first pass of a multipass weld.

SEMI-AUTOMATIC ARC WELDING - Arc welding with equipment which controls only the filler-metal feed. The advance of the welding is manually controlled.

SHIELDED METAL-ARC WELDING - An arc-welding process in which fusion is obtained by heating with an electric arc between a covered metal electrode and the work. Decomposition of the electrode provides shielding. Pressure is not used and filler metal is obtained from the electrode.

SHIELDING GAS - A gas which is used to protect the arc and the weld puddle from the atmosphere during arc welding.

SHORT-CIRCUITING TRANSFER - See dip transfer.

SINGLE-BEVEL GROOVE WELD - A type of groove weld. See Figure 84.

SINGLE-J GROOVE WELD - A type of groove weld. See Figure 88.

SINGLE PASS WELD - A weld in which only one layer of weld metal is used.

SINGLE-U GROOVE WELD - A type of groove weld. See Figure 86.

SINGLE-VEE GROOVE WELD - A type of groove weld. See Figure 82.

SLAG - In welding, consists of materials which blanket the weld to prevent oxidation of the molten metal and to remove impurities from the weld pool.

SLAG INCLUSION - Nonmetallic solid material entrapped in weld metal or between weld metal and base metal.

SLOT WELD - A weld made in an elongated hole in one member of a lap or tee joint joining that member to that portion of the surface of the other member which is exposed through the hole. The hole may be open at one end and may be partially or completely filled with weld metal.

SOLDERING - A joining process in which a bond is obtained by filling the joint with fusible alloys of relatively low melting temperature.

SOLID-PHASE BONDING - Those processes in which joining is accomplished without changing the base metals from the solid state and without the use of a liquid filler metal. Pressure is usually used. Heating may be used, but none of the components reach the molten state.

SPATTER - In arc and gas welding, the metal particles expelled during welding which do not form a part of the weld.

SPOT WELDING - A welding process in which fusion of the faying surfaces is obtained at one spot. This may be accomplished by either resistance- or arc-spot welding techniques.

SPRAY TRANSFER - The type of metal transfer in which the metal leaves the electrode in the form of a fine, uniform spray, as opposed to globular transfer.

SPREAD-ARC WELDING - A form of submerged-arc welding in which the electrode is automatically oscillated in a direction at right angles to the direction of travel. This results in a wide, flat weld bead.

SQUARE-GROOVE WELD - A type of groove weld. See Figure 81.

STICK-OUT - See electrode extension.

STRAIGHT POLARITY - The arrangement of direct-current arc welding in which the work is the positive pole and the electrode the negative pole.

STRAIN - Distortion of deformation of a metal structure due to stress.

STRENGTH - The ability of a material to resist strain.

STRESS - Force producing or tending to produce deformation of a metal.

STRESS RELIEVING - Uniform heating of a structure or portion thereof to a sufficient temperature, below the critical range, to relieve the major portion of the residual stresses, followed by uniform cooling.

STRINGER BEAD - A type of weld bead made without appreciable transverse oscillation.

STRIP-ELECTRODE WELDING - A variation of submerged-arc welding which uses a thin, wide strip as an electrode, rather than the conventional wire.

STUD GUN - A gun used in stud welding.

STUD WELDING - An arc-welding process for joining metal stud, or similar part to another workpiece. Fusion is produced by drawing an electric arc between the parts as they are brought together under pressure.

SUBMERGED-ARC WELDING - An arc-welding process in which fusion is obtained by heating with an electric arc or arcs between a bare metal electrode or electrodes and the work. Shielding is provided by a blanket of granular, fusible material on the work. Pressure is not used and filler metal is obtained from the electrode or a supplementary welding rod.

SURFACE TENSION - A property of liquids in which the exposed surface tends to contract to the smallest possible area, as in the spheroidal formation of drops.

SURFACING - The deposition of filler metal on a metal surface to obtain a buildup of material having desired corrosion resistance or wear properties or to restore the part to desired dimensions. See Figure 80.

TACK WELD - A weld made to hold parts of a weldment in proper alignment until the final welds are made.

TEE JOINT - A joint between two members located approximately at right angles to one another in the form of a T. See Figure 81.

TEMPERING - A heat treatment of steels performed after hardening to partially restore ductility. The steel is heated to a temperature below the critical range followed by any desired rate of cooling.

TENSILE STRENGTH - The resistance to breaking which metals offer when subjected to a pulling stress.

THROAT - The shortest distance from the root of a fillet weld to its face.

TOE OF WELD - The junction between the face of a weld and the base metal.

TORCH - See welding torch.

TOUGHNESS - The resistance of a material to fracture after permanent deformation has begun.

TRANSFERRED ARC - In plasma-arc welding, an arc established between the work and an electrode within the torch.

TRAVEL SPEED - See weld travel speed.

UNDERBEAD CRACK - A crack in the base metal heat-affected zone not extending to the surface of the base metal.

UNDERCUT - A groove melted into the base metal adjacent to the toe of a weld and left unfilled by weld metal.

VERTICAL POSITION - The position of welding in which the axis of the weld is approximately vertical. See Figures 97, 98.

VERTICAL SUBMERGED-ARC WELDING - A submerged-arc welding process in which the weld is made in the vertical position between two plates.

WELD - A localized coalescence of metal in which fusion is produced by heating to suitable temperatures, with or without the application of pressure, and with or without the use of filler metal. If used, the filler metal either has a melting point approximately the same as the base metals or has a melting point below that of the base metals but above 800 F.

WELD BACKUP - See backing.

WELD BEAD - A weld metal resulting from a pass.

WELD METAL - That portion of a weld which has been melted during welding.

WELD POOL (PUDDLE) - The pool of molten metal that lies immediately under the electrode during the arc-welding process, which when solidified becomes the weld or fusion zone.

WELD TRAVEL SPEED - The rate at which the welding gun travels across the workpiece, expressed in distance per unit of time, usually inches per minute.

WELDER CERTIFICATION - Certification in writing that a welder has produced welds meeting prescribed standards.

WELDER QUALIFICATION - The demonstration of a welder's ability to produce welds meeting prescribed standards.

WELDING - The metal joining process used in making welds.

WELDING CURRENT - The current flowing through the welding circuit during the making of a weld. In resistance welding, the current used during a preweld or postweld interval is excluded.

WELDING CYCLE - The complete series of events involved in the making of a weld.

WELDING GUN (TORCH) - The device which holds the electrode and carries current to it during arc welding.

WELDING ROD - Filler metal, in wire or rod form, used in gas welding and braze welding, and those arc-welding processes in which the electrode does not furnish any or all of the filler metal.

WELDMENT - An assembly whose component parts are joined by welding.

WIRE-FEED SPEED - The rate at which filler wire is fed into the welding process, expressed in distance per unit of time usually inches per minute.

WORKPIECE - The object which is being welded.

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SPECIFICATIONS AND STANDARDS RELATING TO ARC WELDING

Document Number	Title
Mil-E-278	Electrodes, Welding, Covered, Aluminum Bronze
Mil-E-6843	Electrodes, Welding, Covered, Low-Alloy Steel Primarily for Aircraft and Weapon Applications
Mil-E-8697	Electrode, Welding Coated, Low Hydrogen Heat-Treated Steel
Mil-E-13080	Electrode, Welding, Covered, Austenitic Steel, 19-9 Modified for Armor Applications
Mil-E-13191	Electrodes, Welding, Covered, Bronze, for General Use
Mil-E-15597	Electrodes, Welding, Covered, Coated, Aluminum and Aluminum Alloy
Mil-E-15599	Electrodes, Welding, Covered, Low- and Medium-Carbon Steel
Mil-E-15716	Electrode, Welding, Covered, Molybdenum Alloy Steel Application
Mil-E-16053	Electrodes, Welding, Bare, Aluminum Alloys
Mil-E-16589	Electrode, Welding, Mineral Covered, Low Hydrogen, Chromium-Molybdenum Alloy Steel and Corrosion Resisting Steel
Mil-E-18038	Electrodes, Welding, Mineral Covered, Low Hydrogen, Medium and High Tensile Steel As Welded or Stress-Relieved Weld Application
Mil-E-18193	Electrodes, Welding, Carbon Steel and Alloy Steel, Bare, Coiled
Mil-E-19822	Electrodes, Welding, Bare, High-Yield Steel

Document Number	Title
Mil-E-19933	Electrodes and Rods - Welding, Bare, Chromium-Nickel Steels
Mil-E-21562	Electrodes and Rods - Welding, Bare, Nickel Alloy
Mil-E-21659	Electrodes, Welding, Bare, Copper and Copper Alloy
Mil-E-22091	Electrodes, Welding, Mineral Covered Low Hydrogen High Yield Strength Steel Stress Relieved Weld Application
Mil-E-22200 Supp 1	Electrodes, Welding, Covered, General Specification For
Mil-E-22200/1	Electrodes, Welding, Mineral Covered, Iron-Powder, Low-Hydrogen Medium and High Tensile Steel, As Welded or Stress-Relieved Weld Application
Mil-E-22200/2	Electrodes, Welding, Covered Austenitic Chromium-Nickel Steel for Corrosive and High Temperature Services
Mil-E-22200/3	Electrodes, Welding, Covered, Nickel Base Alloy, and Cobalt Base Alloy
Mil-E-22200/4	Electrodes, Welding, Covered, Copper-Nickel Alloy
Mil-E-22200/5	Electrodes, Welding, Mineral Covered, Iron-Powder, Low-Hydrogen, High Tensile Low Alloy Steel Heat-Treatable Only
Mil-E-22200/6	Electrodes, Welding, Mineral Covered, Low Hydrogen, Medium and High Tensile Steel
Mil-E-22200/7	Electrodes, Welding, Covered, Molybdenum Alloy Steel Application
Mil-E-22749	Electrodes, Bare, and Fluxes, Granular, Submerged Arc Welding, High-Yield Low-Alloy Steels

Document Number	Title
Mil-E-23765 Supp 1	Electrode and Rods - Welding, Bare, Solid General Specification for
Mil-E-23765/1	Electrode and Rod - Welding, Bare, Solid, Mild Steel
Mil-E-23765/2	Electrode and Rod - Welding, Bare, Solid, Low Alloy Steel
Mil-E-45829	Electrode, Welding, Copper, Silicon-Deoxidized, Solid, Bare
Mil-I-6866	Inspection, Penetrant Method of
Mil-I-6868	Inspection Process, Magnetic Particle
Mil-I-8950	Inspection, Ultrasonic, Wrought Material, Process for
Mil-I-23413	Inserts, Welding, Coiled Filler Material, Solid Rings
Mil-I-25135	Inspection Materials Penetrant
Mil-R-11468	Radiographic Inspection, Soundness Requirements for Arc and Gas Welds in Steel
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Mil-W-8604	Welding of Aluminum Alloys, Process for
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Mil-W-21157	Weldment, Steel, Carbon and Low Alloy (Yield Strength 30,000-60,000 Psi)
Mil-W-23680	Welding Set, Arc, Stud
Mil-W-45205	Welding, Inert Gas, Metal Arc, Aluminum Alloys, Readily Weldable for Structures Excluding Armor
Mil-W-45206	Welding, Aluminum Alloy Armor
Mil-W-45210	Welding Resistance, Spot, Weldable Alloys
Mil-W-45211	Welding, Stud, Aluminum
Mil-W-46086	Welding Homogeneous Armor, Metal Arc, Manual
Mil-Std-20	Welding Terms and Definitions
Mil-Std-21	Welded-Joint Designs, Armored-Tank Type
Mil-Std-22	Welded-Joint Designs
Mil-Std-109	Quality Assurance Terms and Definitions
Mil-Std-248 (Navy)	Qualifications for Welders (Other than Aircraft Weldments)
Mil-Std-271	Non-destructive Testing Requirements for Metals
Mil-Std-278	Welding and Inspection of Machinery, Piping and Pressure Vessels for Ships of the United States Navy
Mil-Std-410	Qualification of Inspection Personnel (Magnetic Particle and Penetrant)
Mil-Std-418	Mechanical Tests for Welded Joints

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Mil-Std-437	X-Ray Standard for Bare Aluminum Alloy Electrode Welds
Mil-Std-453	Inspection, Radiographic
Mil-Std-775	X-Ray Standard for Welding Electrode Qualifications and Quality Conformance Test Welds
Mil-Std-779	Reference Radiographs for Steel Fusion Welds
Mil-Std-798	Non-Destructive Testing, Welding, Quality Control, Material Control and Identification and Hi-Shock Test Requirements for Piping System Components for Naval Shipyard Use
Mil-Std-1261	Welding Procedures for Constructional Steels
Navships 250-634-7	Standard Terminology and Definitions for Weld Conditions and Defects
Navships 250-692-2	X-Ray Standards for Production and Repair Welds
Navships 250-1500-1	Standard for Welding of Reactor Coolant and Associated Systems and Components for Naval Nuclear Power Plants
Navships 0900-003-9001	Radiographic Standards for Production and Repair Welds
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AMS 4190	Aluminum Alloy Welding Rod and Wire 5Si
AMS 4191	Aluminum Alloy Welding Rod and Wire 6.3Cu-0.3Mn-0.18Zr-0.15Ti-0.10V
AMS 4395	Magnesium Wire, Welding 9Al-2Zn
AMS 4396	Magnesium Wire, Welding 3.3Ce-2.5Zn-07ZR
AMS 4951	Titanium Wire, Welding
AMS 4953	Titanium Alloy Wire, 5Al-2.5Sn
AMS 4954	Titanium Alloy Welding Wire, 6Al-4V
AMS 5031	Welding Electrodes - 0.07-0.15C - Coated
AMS 5675	Alloy Wire, Corrosion and Heat Resistant Nickel Base 15.5Cr-7Fe-3.1Ti-2.3Mn
AMS 5676	Alloy Wire, Corrosion and Heat Resistant, Nickel Base - 20Cr
AMS 5677	Welding Electrodes, Coated, Alloy, Corrosion and Heat Resistant, Nickel Base 19.5Cr-1.6(Cb +Ta)
AMS 5679	Alloy Wire, Corrosion and Heat Resistant, Nickel Base 15.5Cr-8Fe-2(Cb+Ta)
AMS 5684	Welding Electrodes, Coated, Alloy, Corrosion and Heat Resistant, Nickel Base 15Cr-9Fe-2(Cb+Ta)
AMS 5691	Welding Electrodes, Coated, Steel, Corrosion and Heat Resistant 18Cr-13Ni-2Mo

Document Number	Title
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AMS 5695	Welding Electrodes, Coated, Steel, Corrosion and Heat Resistant 25Cr-20Ni
AMS 5774	Steel Wire, Corrosion and Moderate Heat Resistant 16.5Cr-4.5Ni-2.9Mo-0.1N
AMS 5775	Welding Electrodes, Coated, Steel, Corrosion and Moderate Heat Resistant 16.5Cr-4.5Ni-2.9Mo-0.1N
AMS 5776	Steel Wire, Corrosion Resistant 12.5Cr
AMS 5777	Welding Electrodes, Coated, Steel, Corrosion Resistant 12.5Cr
AMS 5778	Alloy Wire, Corrosion and Heat Resistant, Nickel Base 15.5Cr-2.4Ti-1(Cb+Ta)-0.7A1-7Fe
AMS 5779	Alloy Welding Electrodes, Coated, Corrosion and Heat Resistant, Nickel Base 15Cr-(Cb+Ta)-1.9Ti-0.6A1
AMS 5780	Steel Wire, Corrosion and Moderate Heat Resistant 15.5Cr-4.5Ni-2.9Mo-0.1Mo
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AMS 5785	Welding Electrodes, Coated, Steel, Corrosion and Heat Resistant 29Cr-9Ni
AMS 5786	Alloy Wire, Corrosion and Heat Resistant, Nickel Base 5Cr-24.5Mo-5.5Fe

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AMS 5787	Welding Electrodes, Coated, Alloy, Corrosion and Heat Resistant Nickel Base 4.5Cr-24.5Mo-5.5Fe
AMS 5795	Welding Electrodes, Coated, Alloy, Corrosion and Heat Resistant Iron Base 20Cr-20Ni-20Co-3Mo-2W-1(Cb+Ta)
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American Welding Society and
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